THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

A Framework for Systematic use of Realistic Visualisation to Support Layout Planning of Production Systems

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Cover:
The framework for systematic use of realistic visualisation to support layout planning of production systems, see section 5.1.

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Abstract

The process of designing production systems comprises a sequence of steps toward the final design and realisation. Layout planning is a significant part of this process. Its outcome should be a layout which matches the existing spatial conditions of the factory building and desired performance of the production system. To support layout planning, virtual representations of layouts can be created to plan and evaluate layout alternatives. Costly problems can arise during the realisation, if the virtual representations are inaccurate or lack details of the factory building and planned production systems. 3D laser scanning can be used to create accurate and detailed virtual representations by capturing the spatial conditions of existing factory buildings. The data from a 3D laser scan can be used for realistic visualisation of the existing factory building. If this is combined with 3D CAD models of new equipment, the planned production system layout can also be visualised realistically. Realistic visualisation has been shown to enable accurate planning and evaluation of production system layouts, but it does require a systematic working method.

The aim of this thesis is to outline and evaluate a framework for systematic use of realistic visualisation to support layout planning of production systems. This aim is addressed using an action research design; this incorporates five industrial studies targeting industrial projects designing production systems. The framework is outlined and evaluated based on the results of the industrial studies.

The outlined framework follows a project model for production systems design. It includes several design activities which rely on realistic visualisation of the planned production system layouts. The framework can be used to support the layout planning of industrial projects designing production systems. Its outcomes include making the correct decisions, reducing costly risks and problems and reducing overall project time. Layout planning supported by realistic visualisation allows manufacturing companies to reduce uncertainty when realising planned production systems.

Keywords: *production systems, manufacturing systems, layout planning, 3D laser scanning, point clouds, visualisation.*

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Erik Lindskog

Gothenburg, Sweden, February 2018

List of appended papers

Paper I **Lean Based Problem Solving using 3D Laser Scanned Visualizations of Production Systems**
Lindskog, E., Berglund, J., Vallhagen, J., and Johansson, B.
International Journal of Engineering Science and Innovative Technology, 2014, Vol. 3 No. 3

Paper II **Production Systems Redesign using Realistic Visualisation**
Lindskog, E., Vallhagen, J., and Johansson, B.
International Journal of Production Research, 2017, Vol. 55 No. 3

Paper III **Lessons Learned from 3D Laser Scanning of Production Systems**
Lindskog, E., Berglund, J., Johansson, B., and Vallhagen, J.
Proceedings of the 6th International Swedish Production Symposium 2014

Paper IV **Improving Lean Design of Production Systems by Visualization Support**
Lindskog, E., Vallhagen, J., Berglund, J., and Johansson, B.
Proceedings of the 48th CIRP Conference on Manufacturing Systems 2015

Paper V **Layout Planning and Geometry Analysis using 3D Laser Scanning in Production System Redesign**
Lindskog, E., Berglund, J., Vallhagen, J., and Johansson, B.
Proceedings of the 6th CIRP Conference on Assembly Technologies and Systems 2016

Paper VI **Realistic Virtual Models for Factory Layout Planning**
Nåfors, D., Lindskog, E., Berglund, J., Gong, L., Johansson, B., and Vallhagen, J.
Proceedings of the 2017 Winter Simulation Conference

List of additional papers

A Method for Determining the Environmental Footprint of Industrial Products Using Simulation
Lindskog, E., Lundh, L., Berglund, J., Lee, T., Skoogh, A., and Johansson, B.
Proceedings of the 2011 Winter Simulation Conference

3D Movie Creation from Discrete Event Simulation Software Models of Manufacturing Industries
Faure, L., Koochakan, A., Berglund, J., Lindskog, E., and Johansson, B.
Proceedings of the International Conference of Modeling, Optimization and Simulation 2012

Evaluation and Calculation of Dynamics in Environmental Impact Assessment
Johansson, B., Andersson, J., Lindskog, E., Berglund, J., and Skoogh, A.
Proceedings of the Advances in Production Management Systems 2012

Combining Point Cloud Technologies with Discrete Event Simulation
Lindskog, E., Berglund, J., Vallhagen, J., Berlin, R., and Johansson, B.
Proceedings of the 2012 Winter Simulation Conference

Supply Chain Carbon Footprint Tradeoffs Using Simulation
Jain, S., Lindskog, E., and Johansson, B.
Proceedings of the 2012 Winter Simulation Conference

Visualization Support for Virtual Redesign of Manufacturing Systems
Lindskog, E., Berglund, J., Vallhagen, J., and Johansson, B.
Proceedings of the 46th CIRP Conference on Manufacturing Systems 2013

A Hierarchical Approach for Evaluating Energy Trade-offs in Supply Chains
Sanjay, J., Lindskog, E., Andersson, J., and Johansson, B.
International Journal of Production Economics, 2013, Vol. 146 No. 2

Multi-Resolution Modeling for Supply Chain Sustainability Analysis
Sanjay, J., Sigurðardóttir, S., Lindskog, E., Andersson, J., Skoogh, A., and Johansson, B.
Proceedings of the 2013 Winter Simulation Conference

Using 3D Laser Scanning to Support Discrete Event Simulation of Production Systems: Lessons Learned
Berglund, J., Lindskog, E., Johansson, B., and Vallhagen, J.
Proceedings of the 2014 Winter Simulation Conference

On the Trade-off Between Data Density and Data Capture Duration in 3D Laser Scanning for Production System Engineering
Berglund, J., Lindskog, E., and Johansson, B.
Proceedings of the 48th CIRP Conference on Manufacturing Systems 2015

Production System Geometry Assurance Using 3D Imaging
Berglund, J., Lindskog, E., Vallhagen, J., Wang, Z., Berlin, C., and Johansson, B.
Proceedings of the 6th CIRP Conference on Assembly Technologies and Systems 2016

List of abbreviations

2D	Two-dimensional
3D	Three-dimensional
BIM	Building Intelligence Management
CAD	Computer Aided Design
CNC	Computer Numerical Control
DES	Discrete Event Simulation
HMD	Head-Mounted Display
IS-GDP	Information System Global Development Process
LAMDA	Look Ask Model Discuss Act
RGB	Red Green Blue
VR	Virtual Reality
VSM	Value Stream Mapping
SLP	Systematic Layout Planning

Table of contents

1 Introduction

This chapter introduces the research area and positioning of this thesis within it. The aim and research questions are then formulated based on that positioning. A presentation follows, detailing the context, scope, delimitations and activities of the research. The chapter then concludes with an outline of the thesis.

1.1 Background

Manufacturing companies are continuously facing new challenges, such as product introductions, changing market demands and performance improvements (Jung et al., 2017). Companies can address these challenges by redesigning their existing production systems (with minor changes) or designing new ones (Jung et al., 2017). The comprehensive process of designing production systems is typically project-structured, comprising numerous factors and problems to consider (Schuh et al., 2011). Making the decision-making one of the most important tasks (Chryssolouris, 2006). Layout planning is one part of the process and must be finalised before any physical installations can start (Heragu, 2008). The goals of layout planning are to minimise material handling and provide a safe work environment. This means such things as determining the location of machines, workstations and other departments (Heragu, 2008). An efficient production system layout is critical to performance and can reduce overall costs (Heragu, 2008; Sule, 2008).

The process of designing production systems may involve the use of virtual tools (as in computer applications) to address different areas and problems. One such area where specific virtual tools are used is layout planning (Schuh et al., 2011). Virtual tools are used to forecast, analyse and visualise production system layouts and thus identify and prevent potential problems before realisation (Onosato and Iwata, 1993). Virtual tools are an important aid in making correct decisions during the design process (Zhu and Chen, 2008). Despite the use of virtual tools, problems are detected during and after the realisation. An example of a layout problem might be when a machine is given insufficient physical space in its planned location, resulting in costly relocation of the machine or other equipment (Date and Rebello de Andrade, 2015). This type of problem may be down to inaccurate virtual representations of the production systems (Berglund et al., 2016). This can derive from modelling difficulties, incomplete details in the representations or measurement errors in the existing factory building.

The virtual representations used in virtual tools for layout planning need to be accurate to the existing factory building and production system. Such virtual representations can be re-formed by using terrestrial 3D laser scanning to capture spatial data of existing factory buildings and production systems, in an almost 360° field of view (Aurich et al., 2009; Gregor et al., 2009; Shellshear et al., 2015). The 3D laser scanners generate accurate virtual 3D representations of the captured environments. These can be used for several different purposes when designing productions systems or sections of them (Lindskog, 2014; Simonsson and Johansson, 2015). In layout planning, 3D laser scan data can be used to ensure that the planning remains accurate to the conditions of the existing factory building.

Realistic[1] visualisation was introduced in Lindskog (2014) for use in discussion and decision-making support during projects designing production systems. The purpose of realistic visualisation is to reduce the barriers and differences between the real production system, its virtual representation and the mental model of it, as introduced in Figure 1-1. Virtual representations based on 3D laser scan data on existing conditions can be created and then used in realistic visualisation. These are accurate and can be understood by the various experts involved in production systems design. In Lindskog (2014) it was shown that realistic visualisation can support different phases and tasks in industrial projects designing production systems. Exploiting the opportunities of realistic visualisation requires a structured way of working that can support the layout planning involved in such projects.

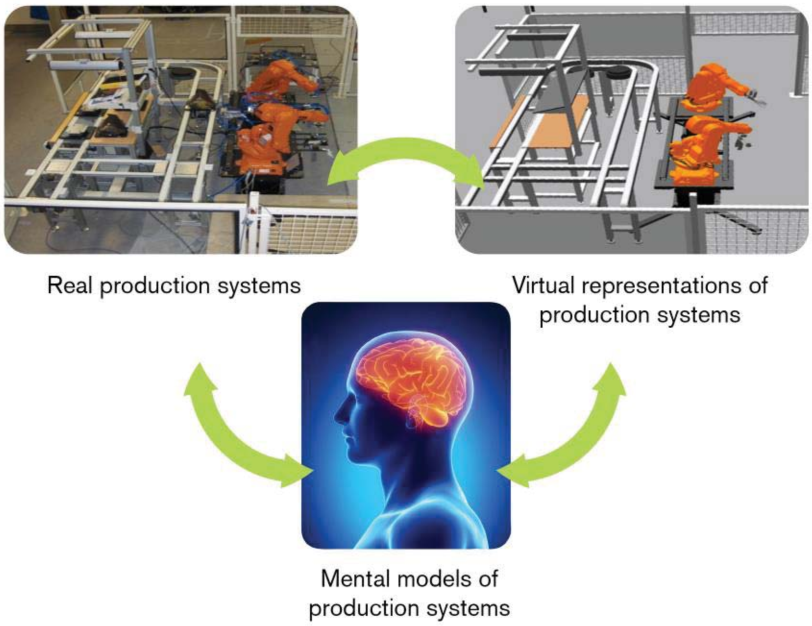

Figure 1-1: The relationship between the mental model, virtual representation and real production system.

[1] "Realistic" is defined as "representations of objects that are presented in such a way that they are accurate and true to life" (Oxford Dictionaries, 2013).

1.2 Aim

This thesis aims to outline and evaluate a framework for systematic use of realistic visualisation to support layout planning of production systems.

1.3 Research questions

Three research questions (RQs) have been formulated to achieve the aim.

The first RQ addresses pre-requisites for a framework, covering the needs and drivers from an industrial perspective.

> ***RQ1:*** *What functions are desirable in a framework for systematic use of realistic visualisation to support layout planning of production systems?*

The second RQ addresses the outlining of the framework to match a project model for production systems design.

> ***RQ2:*** *How can a framework for systematic use of realistic visualisation to support layout planning of production systems be outlined to fit an industrial perspective?*

The third RQ addresses the evaluation of the outlined framework to identify the benefits and challenges before it can be utilised.

> ***RQ3:*** *What are the benefits and challenges in utilising a framework for systematic use of realistic visualisation to support layout planning of production systems?*

1.4 Research context, scope and delimitations

The research has been carried out mainly in collaboration with GKN Aerospace Engine Systems (referred to as the Company in this thesis). The Company produces high-end engine components for the aerospace industry. This requires the Company's production systems to deal with long product life-cycles and extreme quality requirements. Such requirements give rise to unique conditions, with mixed product programmes handling components for old and new engines. The production process technologies may change over time and need to be adapted to the old engine components. Production processes cannot always be changed and this results in a wide variety of production methods for different components. The variety of methods (combined with variable demand and volumes) creates rather complex situations which must be dealt with when designing production systems. The Company's production systems are mainly organised as functional layouts, but its vision is to change towards more product-orientated layouts.

The scope of the research is to provide layout planning support for industrial projects designing production systems in existing factory buildings. These industrial projects may involve redesigning existing production systems or designing new ones. The production systems addressed are organised as functional layouts, with mostly standalone machines and equipment.

The delimitations of the research are as follows:

- Realistic visualisation covers a static view of the production systems. Simulation or animation will not be the focus.
- Off-the-shelf 3D laser scanning equipment and computer applications will be used; no applications will be developed by the author of this thesis.
- Group dynamics and formation of groups for production systems design will not be covered.
- Empirical data from the industrial studies covered in this thesis has been collected from a single company.

1.5 Research activities

The research was part of two research projects: 1) Visual Production and 2) Methodology for Visual Production Development. These were initialised in 2011 and 2014 respectively, with the Company. The overall purpose of these research projects was to increase efficiency and effectiveness by using realistic visualisation for production systems design. The underlying concept was for a group of experts to transform themselves virtually into the planned production system and make correct decisions together. During the research projects, industrial projects tasked with layout planning of production systems were studied at the Company. These projects were addressed within five industrial studies carried out between 2011 and 2017, as per the timeline in Figure 1-2. The industrial studies are reported in the appended papers and summarised in this thesis.

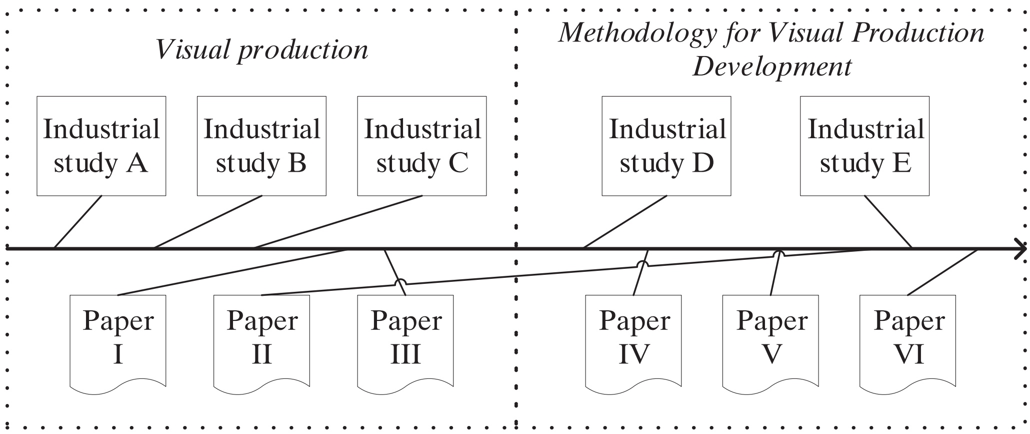

Figure 1-2: The timeline of research projects, industrial studies and appended papers (per publication year).

The appended papers include one or more of the industrial studies, as presented in Table 1-1. Several of the industrial studies appear in more than one paper. However, the ways in which the empirical data is analysed and the take-away from the studies differ from paper to paper. Additional industrial studies are described in the appended papers but will be not presented in this thesis because the author of this thesis role in them was minor. However, the additional studies have influenced the overall results and the lessons learned are transferred between the studies.

Table 1-1: The relationship between the appended papers and the industrial studies.

	Industrial study				
	A	**B**	**C**	**D**	**E**
Paper I			X		
Paper II	X	X	X		
Paper III	X	X	X		
Paper IV				X	
Paper V		X[2]	X[3]	X	
Paper VI					X

1.6 Thesis outline

This thesis consists of seven additional chapters with the following content.

Chapter 2 – Frame of reference: presents the frame of reference, starting with the overall production system design and focusing on layout planning. This is followed by a section presenting virtual tools used to support the production system design and a further section presenting the 3D laser scanning.

Chapter 3 – Research approach: presents the research approach and methods applied in answering the research questions and fulfilling the aim. The chapter starts by defining the research and then describes the research design, methods of data collection, data analysis and the research quality.

Chapter 4 – Framework functions identification: summarises the first four industrial studies and offers overall reflections on them. The aim is to compile a list of desired functions in a framework for systematic use of realistic visualisation to support layout planning of production systems.

Chapter 5 – Framework outline: presents the outline of the framework for systematic use of realistic visualisation to support layout planning of production systems.

Chapter 6 – Framework evaluation: presents the evaluation of the framework for systematic use of realistic visualisation to support layout planning of production systems. This evaluation was done during the fifth industrial study.

Chapter 7 – Discussion: discusses the results in relation to other research in the area, the research approach and potential future research.

Chapter 8 – Conclusion: presents the conclusions drawn from the research.

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[2] Presented as Industrial study A in Paper V.
[3] Presented as Industrial study B in Paper V.

2 Frame of reference

This chapter presents the frame of reference, starting with the overall production system design and focusing on layout planning. This is followed by a section presenting virtual tools used to support the production system design and a further section presenting the 3D laser scanning.

2.1 Production system design

The process of designing production systems relates to different terms used in the literature, depending on the author, publication and context. One such related term used within the area is "facility planning". This is defined by Wiendahl and Nyhuis (2014) as the process of planning a factory from the first idea and up to the start of production. Facility planning is divided into seven fields with four main cores, as presented in Figure 2-1 (Wiendahl and Nyhuis, 2014).

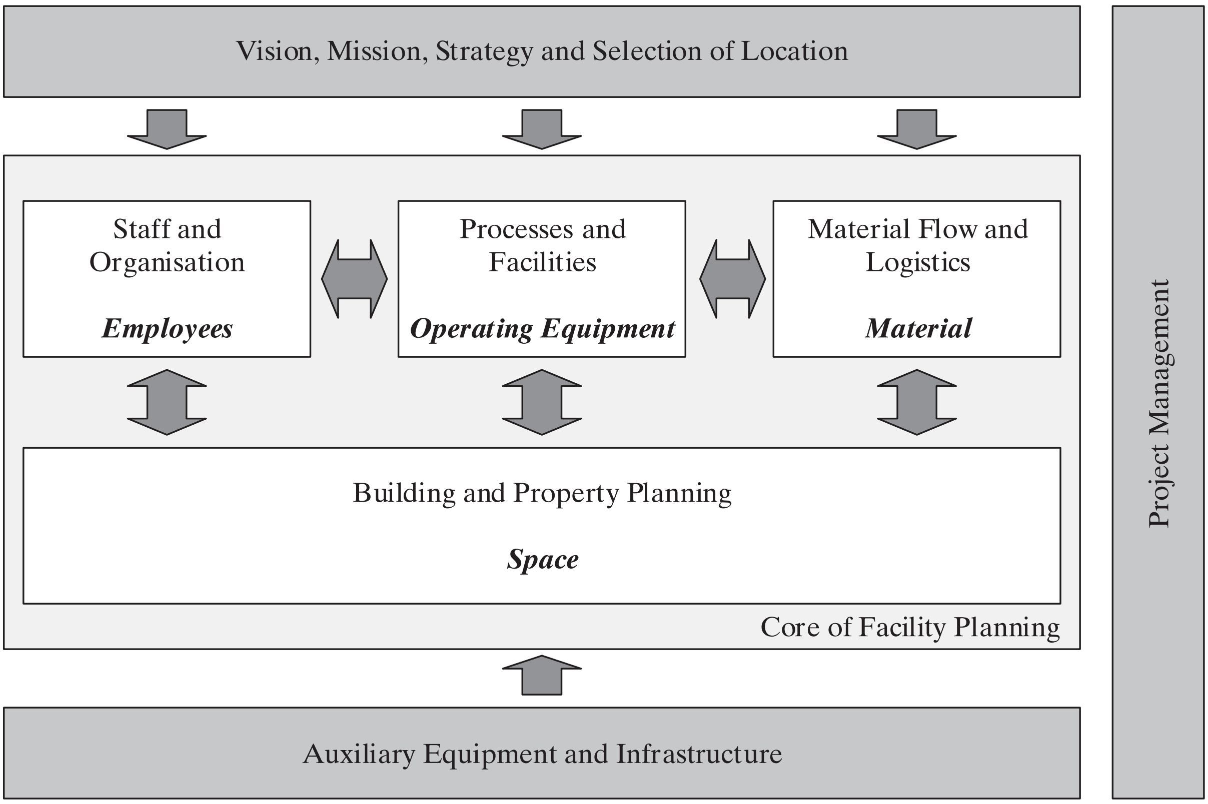

Figure 2-1: Fields of facility planning, adapted from Wiendahl and Nyhuis (2014).

Facility planning is applicable in a number of different contexts, such as hospitals, production plants, warehouses, airports, retail stores, schools, banks or offices (Tompkins et al. 1996). In the context of planning a manufacturing facility, this process can be divided into the areas of plant location and plant design, as presented in Figure 2-2. Plant design is further divided into plant facility system, plant layout and material handling.

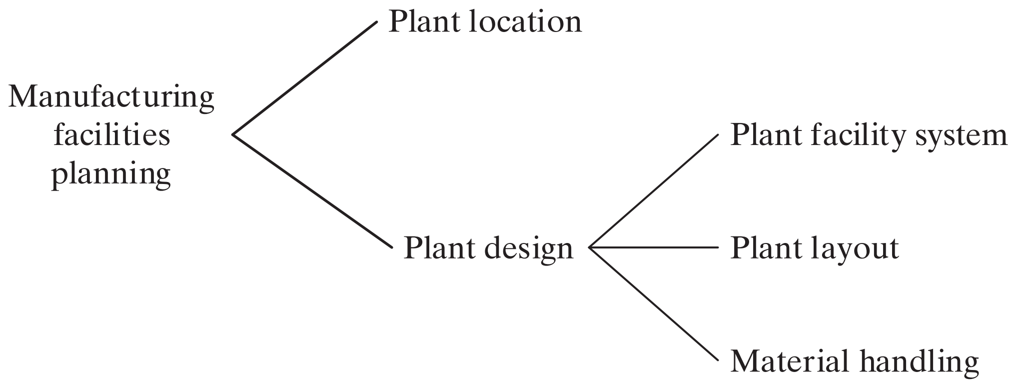

Figure 2-2: The hierarchy of manufacturing facilities planning, adapted from Tompkins et al. (1996).

Chryssolouris (2006) describes manufacturing systems design in similar fashion to the way Tompkins et al. (1996) discuss the plant design aspects of planning manufacturing facilities. The process of manufacturing systems design is divided into four sub-problem areas: resource requirements, resource layout, material flow and buffer capacity (Chryssolouris, 2006). These are presented in Figure 2-3 and can be related to the areas of plant design by Tompkins et al. (1996).

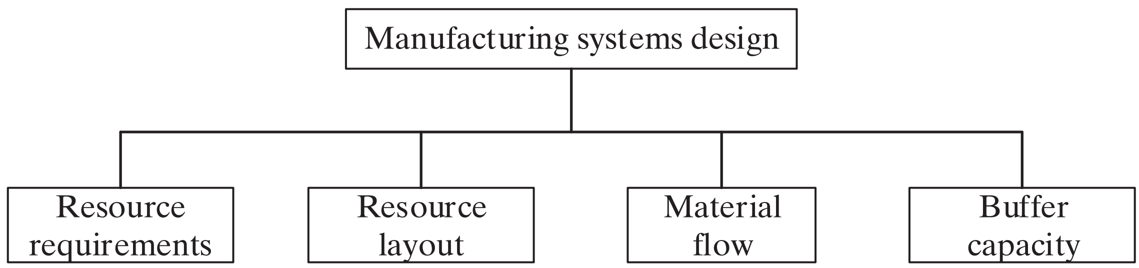

Figure 2-3: Sub-problem areas of manufacturing systems design, adapted from Chryssolouris (2006).

A manufacturing system is defined by Chryssolouris (2006) as a combination of humans, machinery and equipment bound by a common flow of material and information. This definition is used in this thesis to describe a production system. Production systems and manufacturing systems may be synonyms or they may describe different system levels. In this thesis, a manufacturing system is a superior to a production system, as presented in Figure 2-4. Bellgran and Säfsten (2010) use "production development" to describe the design and its realisation, including the building and industrialisation of production systems (Bellgran and Säfsten, 2010). This process is considered a part of the product realisation process, meaning the process from product planning to complete product (Bellgran and Säfsten, 2010).

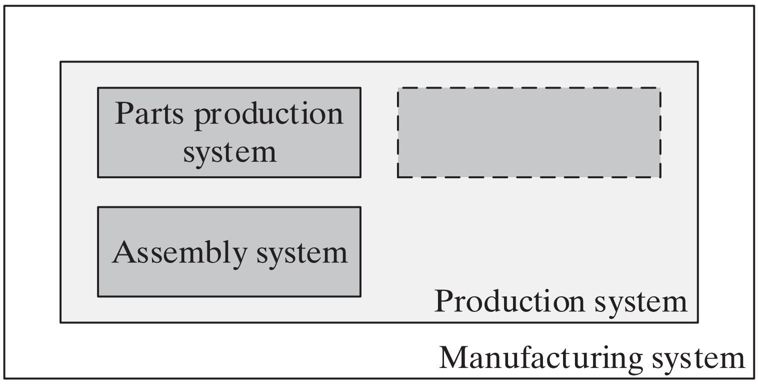

Figure 2-4: The hierarchical perspective on a production system, adapted from Bellgran and Säfsten (2010).

As presented by Tompkins et al. (1996) and Chryssolouris (2006), layout planning is one of the main areas to address when designing production systems. The layout planning can be categorised into two types of problems: design and optimisation (Heragu, 2008). Problems consider the physical design of the layout and are often subjective, based on engineers' previous experience. Optimisation problems are mathematical and use algorithms to suggest an optimal theoretical layout. The layout planning described in the literature is usually theoretical. There is little in the way of practical advice or methods for tackling physical and spatial design that cover all the different considerations and compromises. An example of a practical method is the Systematic Layout Planning (SLP) presented in Muther (1974). Muther (1974) provides hands-on systematic procedures, methods and tools to use when spatially planning layouts. However, the method is complex; it involves several rather detailed steps not fully adapted to today's production systems.

The procedures for layout planning can be divided into two types: construction layout methods or improvement procedures (Tompkins et al., 1996). Construction layout methods involve layout planning in empty factories, while improvement procedures generate updated layouts based on existing production systems (Tompkins et al., 1996). In practice, there are usually constraints to consider. These mean most layout-planning projects involve improvement procedures. Layout-planning projects can be executed on three different levels (Schenk et al. 2010):

- *Level 1:* systematisation of the planning principles in accordance with the planning activities and project definition.
- *Level 2:* implementation of ideal layout planning in accordance with the project development planning activities.
- *Level 3:* implementation of real layout planning in accordance with the project development planning activities taking real restrictions into account.

The above levels of layout planning address three types of layouts: ideal, approximate and real layouts (Schenk et al., 2005). An ideal layout is created with no constraints or restrictions and is the best possible layout. However, this layout is only hypothetical and cannot be implemented. For an approximate layout, some constraints and restrictions are considered, but are intended as an interim step towards a real layout. The real layout considers all constraints and restrictions; it should be possible to implement this layout in a factory building.

2.2 Virtual tools

In recent decades, virtual tools have been used to support various areas of the design process for production systems. Such tools allow changes and design alternatives to be evaluated, without disturbing or impacting existing production systems (Yang et al., 2013). The aim of using virtual tools is to reduce planning time and increase production system quality (Avai et al., 2011). Virtual tools may be visual and numerical, addressing such areas as robotics, machining, logistics planning, material handling and layout planning. Virtual tools can be used to plan and evaluate production system layouts before any physical installations are made (Iqbal and Hashmi, 2001; Yang et al., 2011, 2013). Regardless of the tool type, there are numerous criteria to be considered if a well-functioning and effective layout is to be planned (Dombrowski and Ernst, 2013; Drira et al., 2007).

The use of visualisation in the virtual tools derives from the fact the human brain processes pictures and models easier than text and numbers (Ebert, 2005). Visualisations which use pictures or models to describe a phenomena increase people's understanding, and can improve training and learning (Gropper, 1963; Pinsky and Wipf, 2000). Understanding is created as a model or imagination in the brain, described as a "mental model" (Schnotz and Kürschner, 2007). Visualisations can be used to support decision-making and has shown to be important in many areas, including city planning, construction and factory planning (Abdul Ghani, 2012; Azhar, 2011; Halatsch et al., 2009; Zhu and Chen, 2008). However, there is a risk that different people will understand the same visualisation differently, due to past experiences interfering with their process of imagination (Dahl et al., 2001). The way visualisations are presented is important to their being understood. For example, when visually evaluating layout alternatives, users gain better perspectives if 3D models are used, rather than 2D ones (Iqbal and Hashmi, 2001).

Collaborative design of production systems can be supported by having visualisation functionalities as part of virtual tools. Among other things, this facilitates better teamwork (Pehlivanis et al., 2004). For visualisations used in collaborative design meetings, it is important to collect information from the discussion immediately. This reduces the risk of losing the information (Saadoun and Sandoval, 1999). Information can be gathered by adapting the virtual representation during meetings. For instance, using a quick modelling process has been shown to facilitate effective decision-making (Pehlivanis et al., 2004). To minimise any misunderstanding of the visualisations, the experts involved in the design process should reach a common understanding that adheres closely to the planned production system (Vallhagen et al., 2011). This collaborative design allows personnel from different areas of an organisation to be included in the decision-making; this means their experience can be brought to bear when evaluating a complex set of sub-designs (Okulicz, 2004).

The virtual representation of an environment can be visualised for single users or groups of users by using Virtual Reality (VR). VR is defined as a 3D virtual environment rendered in real time and controlled by the user (Loeffler and Anderson, 1994). The aim is to give the user a feeling of being inside the 3D virtual environment, with the visualisation using some type of display (Korves and Loftus, 1999). The reason for starting to use VR was the insufficient information provided by traditional 2D models (Smith and Heim, 1999). VR allows accurate and rapid decisions to be made, based on virtual representations in the VR environment (Smith and Heim, 1999). The use of VR in the area of production is quite wide; examples include presenting designs to decision-makers, planning the operation of production systems, training shop-floor personnel and workshops on continuous improvement processes (Aurich et al., 2009; Dangelmaier et al., 2005; Schenk et al., 2005). From a user perspective, VR presented using Head-Mounted Display (HMD) has shown promise in layout planning (Berglund et al., 2017). HMD is one of several technologies used to present VR (Menck et al., 2012). HMD is used to increase the feeling of being inside the virtual representation (Duarte Filho et al., 2010; Menck et al., 2012). The HMD is worn like glasses and the user interacts with the virtual representation via different sensors (Duarte Filho et al., 2010; Korves and Loftus, 2000).

2.3 3D laser scanning

Terrestrial 3D laser scanning is a non-contact technology used for 3D imagining of physical objects and can be used to capture large factory buildings in a short time (Gregor et al., 2009; Lindskog, 2014). There are two main types of terrestrial 3D laser scanners: time-of-flight and phase-shift. Time-of-flight scanners normally capture objects that are more than 100 meters from the scanner. This is suitable for outdoor use, on construction sites for example (Dassot et al., 2011). Phase-shift scanners normally capture objects that are closer than 100 meters from the scanner (Dassot et al., 2011). The field of application determines what scanner type is most suitable. In the field of production systems, objects are captured within a range of up to a few metres. This makes phase-shift scanners most suitable.

2.3.1 History

The first terrestrial 3D laser scanner was introduced to the market in the 1990s with a focus on architecture, engineering and the construction industry (Randall, 2013). Since then, there has been a rapid development of new scanners (Randall, 2013). This development can be divided into four generations of terrestrial 3D laser scanners (Staiger, 2011):

- The *first* generation of scanners (introduced in 1997) was bulky, looked like prototypes and had external data storage and power supply. These scanners used a pulse-based method and had a range of 50-200 m.

- The *second* generation of scanners (introduced in 2002) was faster, but still had external data storage and power supply. The first phase-shift based scanners were introduced during this second generation.
- The *third* generation of scanners (introduced in 2007) had some degree of integrated data storage and power supply. Scanners of this generation had improved measurement speed and the ability to combine digital images with point clouds.
- The *fourth* generation of scanners (introduced in 2009) had fully integrated data storage and power supply. Many scanners also have integrated image cameras as part of the data capturing process. This generation has additional improvements in measurement speed and range.

The development of terrestrial 3D laser scanners had a breakthrough around 2007, when the third generation was introduced. This generation of scanners reduced the time required for each scan and offered increased quality, making it more affordable to use 3D laser scanning. Historically, 3D laser scan data was only monochrome but, with this breakthrough, colour capturing functionality was added as an enhancement to the visualisation (Staiger, 2011). Because 3D laser scanners generate very large data files, it used to be difficult to process the data using ordinary computers. The improved computer performance and software applications made the data processing more effective. These improvements make the scan data more accessible to different users, something known in the field as a "breeding innovation" (Chaffee, 2014).

2.3.2 Technology

Terrestrial 3D laser scanners operate by emitting laser beams and capturing their returned reflection to measure the distance travelled (Klein et al., 2012). Each captured reflection represents a sample of the surface of the closest object along the direction of measurement and is known as a "measurement point" (Klein et al., 2012). Each measurement point stores information about the position as XYZ coordinates, plus the intensity (Staiger, 2003). Typically, the scanners have a field of view of 360° on the horizontal axis and 300-320° on the vertical axis, as illustrated in Figure 2-5 (Dassot et al., 2011). By systematically capturing measurement points in the field of view, the scanner generates a complete spatial representation of the environment. The scanners can capture tens of millions of points in a few minutes (Klein et al., 2012). This systematic capture is known as a "scan". For enhanced visualisation, each measurement point can be complemented with information about the colour of the surface, based on the RGB colour model. This is generated from images taken during each scan by a built-in camera (Staiger, 2011).

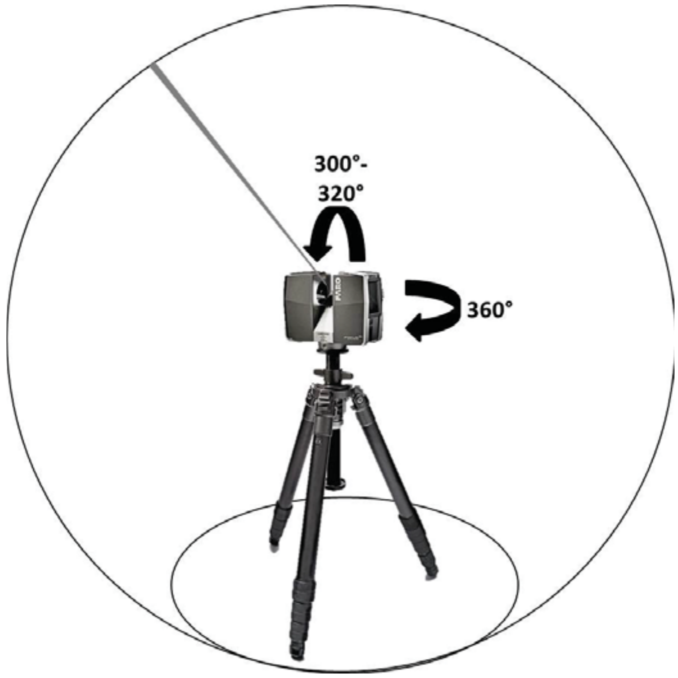

Figure 2-5: Terrestrial 3D laser scanning.

2.3.3 Visualisation

3D laser scan data can be visualised using different computer applications. This thesis distinguishes between two types of visualisation. These types are 1) individual scans as spherical images and 2) all scans combined as a point cloud. Visualising individual scans as spherical images can be described as looking at the captured environment in a panoramic 360° view, comparable to, say, Google Street View. By virtually assuming actual scan locations, it is possible to make measurements and study the captured environment. Spherical images can be provided in standalone or web-based applications, as shown in Figure 2-6. The visualising of 3D laser scan data as point clouds allows measurements and analyses, as well as free movement through the captured environment in 3D. This type of visualisation is typically made using standalone application, as shown in Figure 2-7. These applications allow changes to be visualised in the captured environment, by translating subsets of the point cloud or adding 3D CAD models.

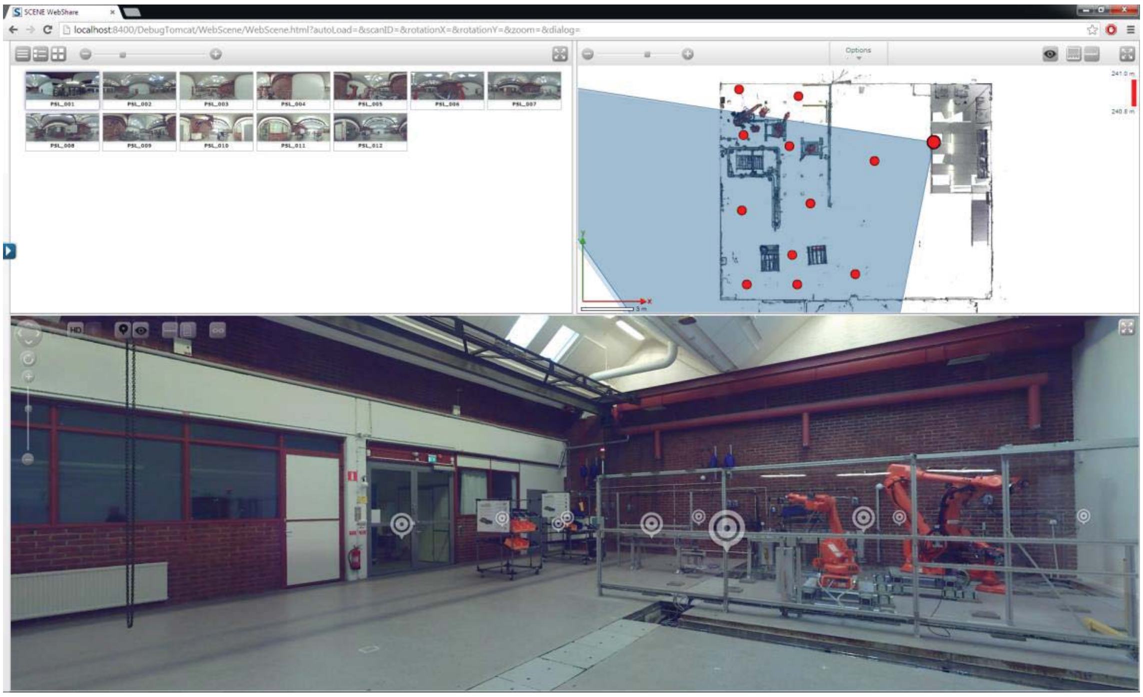

Figure 2-6: Example of 3D laser scan data visualised as spherical images.

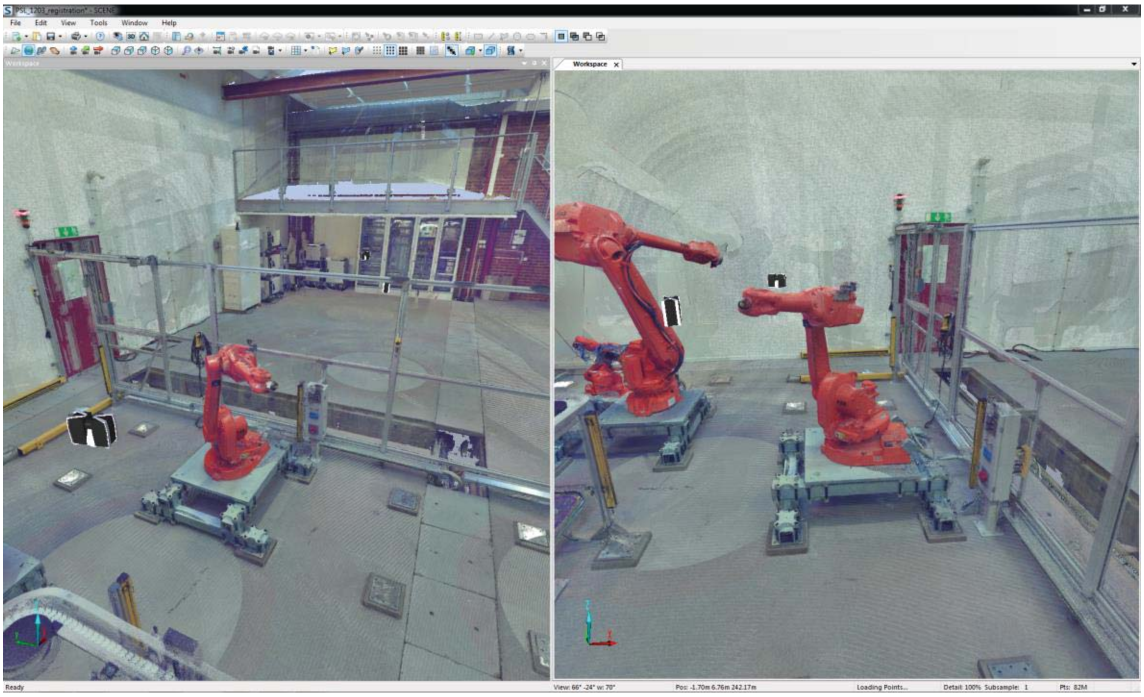

Figure 2-7: Example of 3D laser scan data visualised as a point cloud from two viewpoints.

2.3.4 Application areas

3D laser scanning is applied in various business sectors, to document and digitise physical objects. The terrestrial 3D laser scanning addressed in this thesis originated in surveying but is now applied in business sectors such as architecture, building intelligence management (BIM), facilities management, large object inspections, forensics and heritage preservation (Chaffee, 2014; Sansoni et al., 2009). How 3D laser scan data is used differs between and within business sectors.

For the design, construction and operation of factories, it is generally estimated that terrestrial 3D laser scanning can reduce the total installation cost of brownfield projects by 5-7% (Greaves and Hohner, 2009). Volvo Cars Corporation is an example of a company that has taken the advantages of 3D laser scanning into its production systems design (Farrerons Pericas, 2011; Gorrasi, 2011; Simonsson and Johansson, 2015). All the company's factories have been captured using 3D laser scanning, with the data accessible online to company employees. They use the 3D laser scan data to plan and verify new installations in their production systems, mainly within the body shop (Simonsson and Johansson, 2015). After an installation is made in Volvo's factories, it requires the supplier to make a 3D laser scan of the final installation (Simonsson and Johansson, 2015). The 3D laser scan data of the new installation is then combined with existing data, using incremental updates (Shellshear et al., 2015). Updates like this require a definite infrastructure around the scan data, plus a fixed coordination reference system (Shellshear et al., 2015).

3 Research approach

This chapter presents the research approach and methods applied in answering the research questions and fulfilling the aim. The chapter starts by defining the research and then describes the research design, methods of data collection, data analysis and the research quality.

Research can be defined as a systematic investigation into, and study of, materials and sources in order to establish facts and reach new conclusions (Oxford Dictionaries, 2017). When research is defined, it is typically described as a linear, organised process. However, in practice the process is usually less under control than indicated in the literature (Williamson et al., 2002a). The type of research conducted can be described using distinct categories; the overall distinction being between basic and applied research (Williamson et al., 2002a). Basic research focuses mainly on fundamental theory-building and hypothesis-testing (Williamson et al., 2002a). Applied research strives to solve specific problems in real-life situations (Williamson et al., 2002a). The research in this thesis is classed as applied research, as is most of the research within the production system field. This type of applied research into real-world observations and experiments is also described as empirical research (Flynn et al., 1990).

Deductive and inductive reasoning is used to describe the view or strategy of the research. Deductive reasoning is described as a “hypothesis-testing approach” to research, using existing theory (Bryman and Bell, 2011; Williamson et al., 2002b). Inductive reasoning is described as “hypothesis-generated research”, in which the hypothesis is generated through analysis of data collected through field work and observation (Bryman and Bell, 2011; Williamson et al., 2002b). Inductive reasoning relates to the use of qualitative research methods (as distinct from quantitative reasoning which relates to deductive reasoning) (Creswell, 2014). However, these distinctions should not be taken for granted because the researcher can use a mixture of both methods. Using a mixture of qualitative and quantitative methods is described as a “mixed-methods approach” (Creswell, 2014). The research in this thesis relates to inductive reasoning, with a qualitative approach to data collection based mainly on observations in industrial settings. Suitable research designs for this work include surveys, case study research or action research (Westbrook, 1995).

3.1 Action research

Action research can be used to improve practice or propose new solutions to practical problems, which can be processual problems in organisations (Bryman and Bell, 2011; Oosthuizen, 2002). Such research is usually carried out within a single situation at a time, such as an organisation (Oosthuizen, 2002). An important effect of action research is that it bridges the gap between researchers and practitioners (Bryman and Bell, 2011). Knowledge is simultaneously generated through rigorous research (Oosthuizen, 2002). Action research is closely related to case study research. The main difference between the two is that within case study research, the researcher is an independent observer whilst within action research, the researcher can participate in the system that is to be changed (Westbrook, 1995). An action researcher often becomes a part of the study and may be a member of the organisation being studied (Bryman and Bell, 2011).

The process of action research is typically described as a cycle, which can be iterated to achieve the aim of the research. Oosthuizen (2002) divides the process into four steps: plan, action, results and reflection, as illustrated in Figure 3-1. Having the planning as a part of the research sets action research apart from other research designs, where detailed plans for the entire research project would be laid in advance (Oosthuizen, 2002). Action research allows different methods to be used during the action part of each cycle. Critical reflection on the results is an important part of the cycle and is used to propose a new theory for the action being carried out (Oosthuizen, 2002). Using this reflection, a new cycle can be planned and then commenced, based on knowledge from the previous cycle. This cyclical process can also be described as a spiral, that represents an ongoing iterative process (Hayes, 2011).

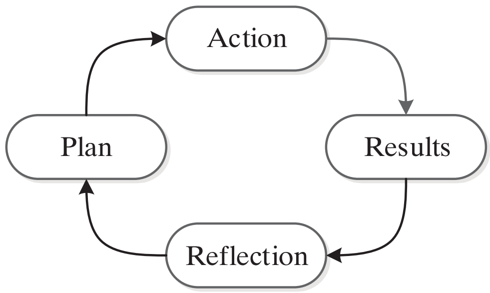

Figure 3-1: A typical action research cycle, adapted from Oosthuizen (2002).

Coughlan and Coghlan (2002) present another view of the action research process, in which the cycle is divided into six steps. These six steps are: data gathering, data feedback, data analysis, action planning, implementation and evaluation (Coughlan and Coghlan, 2002). The research usually consists of several cycles, as illustrated in Figure 3-2. These cycles may be either short, specific events or longer ones (Coughlan and Coghlan, 2002).

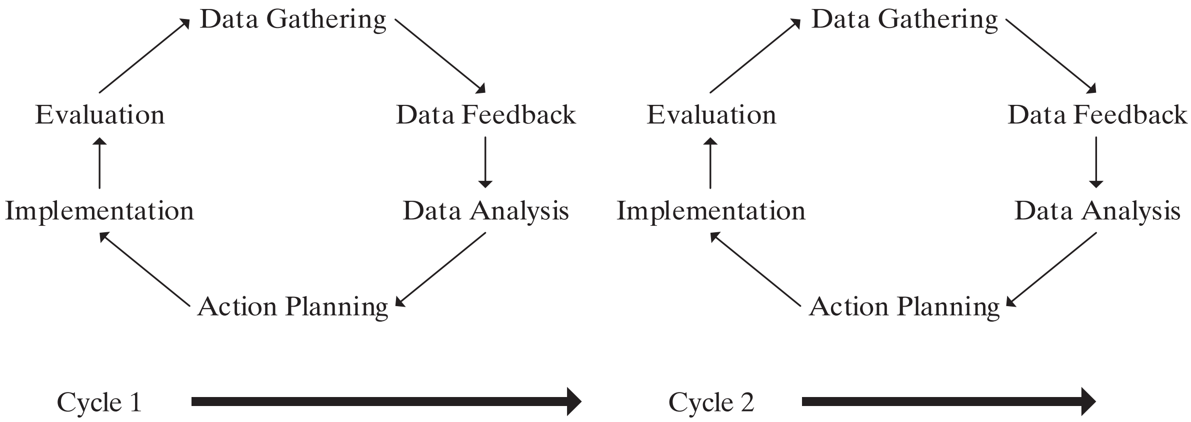

Figure 3-2: Cycles of action research, adapted from Coughlan and Coghlan (2002).

3.2 Data collection

The qualitative approach for collecting empirical data allows the collection of personal reflections and provides a deeper understanding of any problems. The following data collection methods were used to collect the empirical data.

3.2.1 Focus group

Focus group is a data collection method used for listening and collecting information regarding a specific topic such as an issue, service or product (Krueger and Casey, 2000; Morgan, 1996). The purpose of this method is to collect as much experience as possible without pressuring the participants to reach consensus in a discussion (Krueger and Casey, 2000). A moderator is required and play an important role, leading the discussion in the right direction to achieve the aim (Krueger and Casey, 2000; Williamson, 2002a). The discussion should focus on a small number of issues related to a topic predetermined by the researcher (Williamson, 2002a). The recommended group size is seven to twelve people (Williamson, 2002a).

3.2.2 Participant observation

Participant observation is a data collection method for qualitative research. It is used when the researcher is aiming to collect objective data on events or situations (Kawulich, 2005; Mack et al., 2005). This method allows the researcher to gain insight into context, relationships and behaviours (Mack et al., 2005). However, participant observation can be rather time-consuming and the documentation relies on memory, personal discipline and researcher diligence (Mack et al., 2005). The method is inherently subjective and requires the researcher to make a conscious effort to maintain objectivity (Mack et al., 2005).

Within the scope of participant observation, there are four stances the observer can assume. These are: complete observer, observer-as-participant, participant-as-observer and full participant, as illustrated in Figure 3-3 (Bow, 2002; Kawulich, 2005). To be a full participant, the researcher needs to be a member of the group being studied (Bow, 2002; Kawulich, 2005). However, they must conceal the role as a researcher to avoid disrupting normal activity (Bow, 2002; Kawulich, 2005). A participant-as-observer is an observer who interacts quite extensively with the participants and is a member of the group being observed (Bow, 2002; Kawulich, 2005). An observer-as-participant may participate in group activities if desired, but the researcher's main role is to collect data by observing the group (Bow, 2002; Kawulich, 2005). A complete observer is a researcher who is completely hidden from the group and unknown to the group being studied (Bow, 2002; Kawulich, 2005).

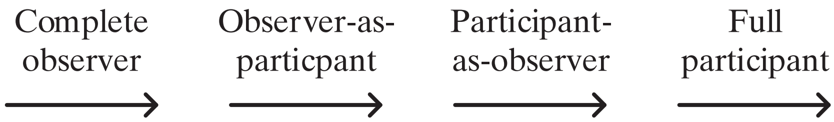

Figure 3-3: Participant observation stances, adapted from Bow (2002).

3.2.3 Interviews

Interviews are a data collection method mainly used for qualitative data. Interviews are divided into three distinct types, depending on the design and execution. Structured interviews follow a fixed sequence and use the same questions in each interview session (Williamson, 2002b). This type is typically used when it is important to be able to compare the results across the different sessions. Semi-structured interviews have a predefined list of questions, but allow for the interviewer to ask follow-up questions (Dicicco-Bloom and Crabtree, 2006; Williamson, 2002b). This type provides an in-depth understanding on a specific question or topic with one interviewee or groups of interviewees during structured discussions. However, it still ensures the same focus is maintained across multiple interview sessions (Dicicco-Bloom and Crabtree, 2006). Unstructured interviews do not follow any predefined structure or questions (Dicicco-Bloom and Crabtree, 2006; Williamson, 2002b). The questions are generated from the previous answer. This type of interview is suitable for exploring a subject or gaining insight into people (Williamson, 2002b).

3.3 Spatial data capture

The spatial data of a factory building can be captured using terrestrial 3D laser scanning. Scans from several positions are usually required to capture a complete environment. The positions of the scanner need to be planned to ensure that all necessary data can be captured. It is important to consider the line of sight from the scanner to the objects of interest. For reliable results, the scan area should remain motionless throughout the scanning process. The different scans are later combined into one dataset during a semi-automated registration process, using either reference objects or cloud-to-cloud analysis. When using reference objects, at least three corresponding reference objects need to be visible in two scans for them to be combined successfully. Examples of reference objects are white spheres or black and white checkerboards; these should be placed in the area to be captured. For cloud-to-cloud registration, the scans are combined by analysing the overlap between the scans to align them correctly.

The size of the final dataset from the registration process depends on the resolution setting in the scanner; it may vary from a few thousand to billions of individual measurement points. This dataset can be used to generate a point cloud consisting of all the individual measurement points. The resulting point cloud can be made sparser by filtering away a percentage of the points. This reduces the amount of data and can be done in varying degrees, depending on the target application and processing performance. Unwanted measurement points, such as sensor noise and partially captured moving objects, can be removed by filtering or manual selection. Typical additional operations performed on point clouds are object-based selection and bonding of a subset of points.

3.4 Data analysis

The collected data should be analysed to draw valid inferences that can be used in further research (Blessing and Chakrabarti, 2009). Blessing and Chakrabarti (2009), among others, states that only a few methods are available for analysing qualitative data. However, data analysis is still important if a valid result is to be obtained. The methods used for collecting qualitative data usually result in extensive amounts of raw data to analyse; this is a general difficulty of descriptions using qualitative research (Bryman and Bell, 2011; Pope et al., 2000). The raw data usually comprises field notes, transcriptions or documents (Bryman and Bell, 2011; Pope et al., 2000). Qualitative data analysis is about making sense of the raw data. This means taking it apart as well as putting it together again (Creswell, 2014). The analysis usually begins during the data collection, when the researcher starts generating an understanding of, and relationship to, the raw data and research questions (Bryman and Bell, 2011; Dicicco-Bloom and Crabtree, 2006; Pope et al., 2000). This iterative analysis enables the researcher to get deeper into the topic, by refining the questions during the data collection (Pope et al., 2000). Secondary analysis may be necessary in addition to the analysis of qualitative data collected by the researcher. This involves analysing qualitative data collected by other researchers or organisations, or may involve official statics (Bryman and Bell, 2011).

3.5 Reliability and validity

To make a quality assessment of the research, useful analysis criteria are: reliability and validity (Bryman and Bell, 2011). Empirical data is of little use if its reliability and validity cannot be demonstrated (Flynn et al., 1990).

Reliability is measured as the capability to repeat the methods used and achieve the same result in another study, or repeat study (Flynn et al., 1990). Qualitative data collection methods have practical issues when it concerns repeating studies. There is debate on whether reliability is a suitable quality assessment criterion for qualitative data collection methods. Action research has been criticised as a research design, due to the lack of repeatability (Bryman and Bell, 2011).

Yin (2009) proposes the following three types of validity test to judge the research quality:

- *Construct validity:* identifying correct operational measures for the concepts being studied.
- *Internal validity:* seeking to establish a causal relationship, whereby certain conditions are believed to lead to other conditions (as distinct from spurious relationships).
- *External validity:* defining the domain to which a study's results can be generalised.

Maxwell (2005) proposes a validity test for testing the validity of conclusions and the existence of potential threats to those conclusions. The test consists of eight strategies addressing different validity threats (Maxwell, 2005). The test should be adapted to the study being conducted; not all strategies are always applicable or feasible in a study (Maxwell, 2005). The eight strategies of the validity test are (Maxwell, 2005): intensive, long-term involvement, rich data, respondent validation, intervention, searching for discrepant evidence and negative cases, triangulation, quasi-statistics and comparison.

4 Framework functions identification

This chapter summarises the first four industrial studies and offers overall reflections on them. The aim is to compile a list of desired functions in a framework for systematic use of realistic visualisation to support layout planning of production systems.

Industrial studies A-D were carried out at the Company's factories between 2011 and 2015. These studies addressed industrial projects aimed either at redesigning an existing production system or designing a new one within an existing factory building. The overall aim of the industrial studies was to analyse how realistic visualisation can support such projects and reduce uncertainty in the planned layout. To address this aim, the industrial studies followed an overall research design based on action research. This research design made it possible to build and analyse industrial scenarios in groups of individuals. The researchers were either part of the groups being studied or worked in close collaboration with them. The action research design allowed the industrial studies to be carried out iteratively, with the results from one study leading to the planning of the next one, as illustrated in Figure 4-1.

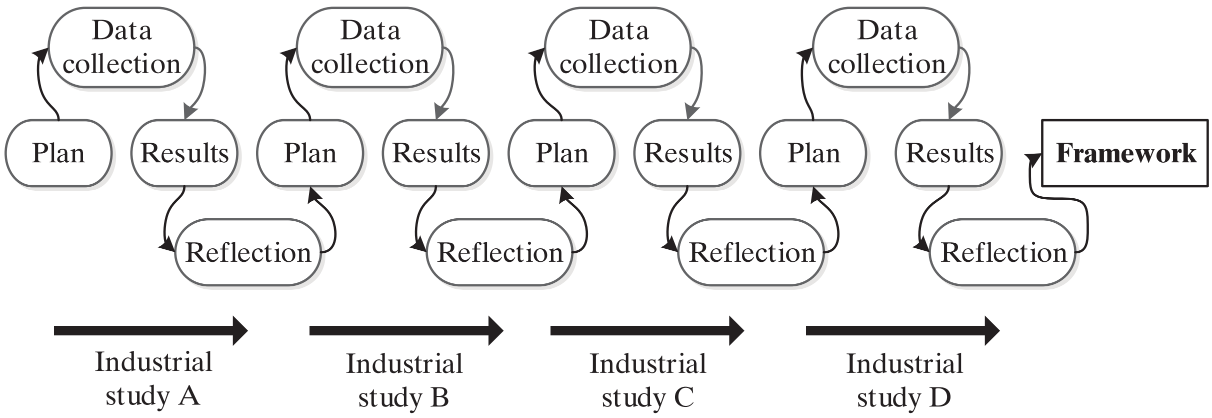

Figure 4-1: The action research of Industrial studies A-D.

Realistic visualisation was used differently in the industrial studies, as presented in Table 4-1. The empirical data in the studies was collected using a variety of methods and represented the action part of the research design, as specified in Table 4-1. Action research allows the methods used to be determined and adapted for each study during the planning stage. The empirical data was analysed and summarised to compile a list of desired functions in a framework for systematic use of realistic visualisation to support layout planning of production systems, to answer RQ1.

Table 4-1: Realistic visualisation and data collection methods used in Industrial studies A-D.

Industrial study	Use of realistic visualisation	Data collection method
A	Visualising an existing factory building during the installation of a planned production system.	Focus group
B	Evaluating machine location and installation in an existing production system.	Participant observation
C	Locating a robotic cell and evaluating work routines within an existing production system.	Interviews
D	Evaluating layout alternatives of a production system within an existing factory building.	Participant observation

4.1 Industrial study A

This industrial study was carried out at the Company's main factory in Sweden with the aim of evaluating possible use of 3D laser scanning to provide a realistic visualisation of an existing factory building. The industrial study is summarised in this section and presented in more detail in Papers II and III.

4.1.1 Plan

The industrial study addressed an industrial project tasked with creating a product-orientated production system within the factory building. The factory building was almost empty at the time of the study and the installation of new machines and equipment had just commenced. The layout of the production system was planned using 2D CAD before the study was initialised.

4.1.2 Data collection

The factory building was captured using 3D laser scanning during work hours and ongoing installation work. Fastener plates for the reference spheres were permanently mounted on pillars to provide the option of using the same positions in future scans. The 3D laser scan data was processed to a point cloud and spherical images of the factory building.

The 3D laser scan data of the existing factory building was visualised during a project meeting, with eight people working on planning and implementing the production system. The focus group method was used to collect ideas and insights from these people on one time-efficient occasion. This method was used to evaluate the potential of using 3D laser scan data as a realistic visualisation of the existing factory building. The meeting participants suggested possible areas of application in their work and problems that could be solved using such data. The research project leader moderated the discussion and the visualisation was controlled by the author of this thesis.

4.1.3 Results

The 3D laser scan data was found to be useful by those working on layout planning and machine acquisition. These people discussed several problems which typically arose while designing production systems and which might be solved using 3D laser scan data. The main problem cited was the lack of accurate and sufficient spatial data of existing production systems and factory buildings. Such data was described as important when making decisions on planned layouts. The currently used 2D CAD layouts were characterised as lacking necessary details, including the height between floor and ceiling, ventilation and the actual space available for a machine. This lack of detail resulted in engineers visiting the factory during meetings, postponing the issues until later meetings or making decisions based on assumptions.

The 3D laser scan data was found to enable virtual viewing of factory buildings with a high degree of accuracy, as exemplified in Figure 4-2. It also meant that problems could be solved during meetings without leaving the room. It was also deemed important for 3D laser scan data to be distributed differently, depending on who was being addressed. For example, a web-based application of spherical images for those interested in collecting basic information and point clouds for those planning the layout.

Figure 4-2: The point cloud used to visualise the factory building.

4.1.4 Reflection

3D laser scanning as a method of capturing existing factory buildings was deemed beneficial to achieving good documentation of the current state, mainly due to the level of accuracy achieved and rapid process. For increased scan data quality, people moving around and construction materials should have been avoided during the scan. Making the scan data available as realistic visualisation (in a project group meeting, for example) allows virtual factory visits. This was deemed a feasible way of working using realistic visualisation. The focus of future studies was set on layout and machine installations. This focus was verified at a workshop held at the Company in connection with the industrial study. Additional people were present to identify what type of information needs to be available. The workshop showed the need to visualise information about the layout and installation. Its results are presented in Lindskog (2014).

4.2 Industrial study B

The industrial study was carried out at the Company's factory in Norway. Its aim was to evaluate how the planned production system layout can be visualised, based on 3D laser scan data. The industrial study is summarised in this section and presented in more detail in Papers II, III and V.

4.2.1 Plan

The industrial study addressed an industrial project tasked with moving an old machine to an empty section in the factory and installing a new machine where the old one had been. This project was the first step of a large project with the overall aim of implementing a product-orientated production system. The project group had previously created a 2D CAD layout of the production system and had some parts of the production system available in 3D CAD.

4.2.2 Data collection

The existing production system was captured using 3D laser scanning with the resulting scan data processed to generate a point cloud. The point cloud was then combined with 3D CAD models of new machines and equipment to create a realistic visualisation, according to the planned 2D CAD layout. The realistic visualisation was used to analyse the planned layout in a project meeting of five people from the Company, all with different relationships to the production system. This is presented in Table 4-2. Participant observation was used to collect empirical data. The author of this thesis acted as a participant-as-observer. Due to technical difficulties in modifying the visualisation, it was necessary for the author to interact with the visualisation. The planned production system layout was discussed within the group and required changes were made to the visualisation. The meeting was documented by the research project leader, acting as an observer-as-participant.

Table 4-2: Industrial participants in the project meeting.

Participant	Work responsibility
1	Manager, production development
2	Engineer, production development
3	Engineer, research and development
4	Engineer, production layouts
5	Machine operator

4.2.3 Results

As exemplified in Figure 4-3, the combination of point cloud and 3D CAD was found useful in visualising the planned production system layout. This type of visualisation gave the group a shared understanding of the planned layout. The varied knowledge and interests of the industrial participants proved important in the discussions and decision-making on solving problems with the planned layout. One such problem was that the new machine and its surrounding equipment required more space than was available. This was solved by allocating available space for some of the equipment in a nearby area. The discussions in the project meeting resulted in a revised layout, with improvements to the work environment, production flow and material handling.

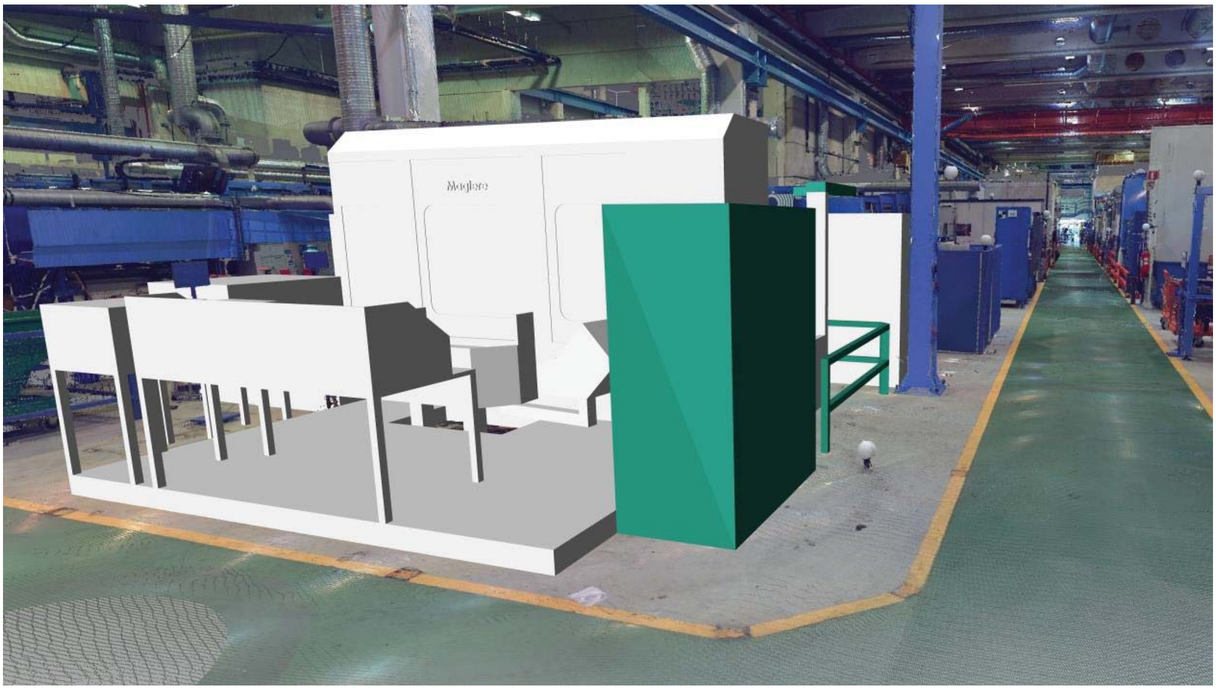

Figure 4-3: The combined point cloud and 3D CAD.

A typical layout problem described in the project meeting was getting a planned layout accepted by the shop-floor personnel. When presenting 2D CAD layouts to shop-floor personnel, they were usually approved. However, once the layouts were realised (even with shop-floor personnel fully apprised) they would not always approve it and costly changes were needed. This type of problem was probably avoided in the industrial study, the machine operator at the meeting having offered pertinent thoughts on how the layout would affect the shop-floor.

4.2.4 Reflection

Combining the point cloud with 3D CAD models for realistic visualisation of the planned layout meant there could be group discussions on the layout, based on a shared understanding. The strength of this type of group discussion is due to the visualisation, plus the gathering of competences from a group of Company people with differing expert knowledge. Realistic visualisation is one suitable tool for discussion and decision-making support. However, the discussions should follow a structured agenda to ensure the focus stays on finding and solving potential problems and risks.

4.3 Industrial study C

This industrial study was carried out in a section of the same factory building as Industrial study A. The aim was to evaluate how realistic visualisation can support layout planning by including 3D laser scan data in a Discrete Event Simulation (DES) model of the production system. The industrial study was carried out in collaboration with Master's students Jansson and Roos (2013). The industrial study is summarised in this section and presented more detailed in Papers I, II, III and V.

4.3.1 Plan

The industrial study addressed an industrial project tasked with improving the production system to meet increased production volume. This production system had been installed since Industrial study A in which, among other things, a robotic cell for automated X-ray inspection of products had been installed. The project group's plan was to install an identical cell to increase the capacity of the production system. The industrial problem was to locate the new cell, based on conditions such as available space, material handling, work environment and capacity specifications. This study targeted the problem using realistic visualisation of the planned production system layout, including the new cell.

4.3.2 Data collection

The existing robotic cell and surrounding area were capturing using 3D laser scanning. Three fastener plates for reference spheres, mounted during Industrial study A, were re-used to align the 3D laser scan data with that of the previous study. The 3D laser scan data of Industrial studies A and C were combined to create a point cloud including a planned location for the new robotic cell. This point cloud was used in a DES model, which included the dynamical aspects of the production system. The DES model was used for realistic visualisation of the planned production system.

The empirical data on how to support the production system design using realistic visualisation was collected during interviews held with Company personnel. These interviews were semi-structured, allowing investigation of a predefined hypothesis in groups consisting of interviewees who shared similar work responsibilities. Four interviews were held with people working in either the production system or the project group responsible for planning and installing the system, as presented in Table 4-3. The interviewers presented two scenarios on how to use realistic visualisation for layout planning of production systems, followed by these questions:

1. What virtual and visual tools are being used today in the development process?
2. What do you think about the presented scenarios?
3. How can the scenarios be related to the redesign process?

Table 4-3: Industrial participants in the four semi-structured interviews.

Interview	Participant	Work responsibility
1	1	Manager, machine acquisition
	2	Project leader, production development
	3	Engineer, production facilities
	4	Engineer, production facilities
2	1	Machine operator
	2	Production technician
3	1	Engineer, simulation of production systems
4	1	Engineer, production logistics
	2	Engineer, production logistics

The interviews were transcribed and analysed by Jansson and Roos (2013). A subsequent, secondary analysis was conducted by the author of this thesis, to draw conclusions.

4.3.3 Results

Problems using 2D CAD to evaluate and visualise layout alternatives were identified during the interviews. Objects such as power cables, pillars and machine equipment were described as not always positioned right or not included at all in the 2D CAD. This caused problems implementing the layout. Another problem described was with everyone included in the planning process understanding the planned layout correctly. This resulted in difficulties communicating and discussing layout alternatives within the Company or with machine suppliers. Providing machine suppliers with the necessary information normally required additional manual measurements in the factory building. Accurately updating the 2D CAD with all necessary information was described as an excessively time-consuming task.

It was found that realistic visualisation enabled accurate layout planning and that layout alternatives could be compared by thoroughly investigating each alternative before making any decisions. Compared to using 2D CAD, this method reduces the time spent evaluating whether equipment fits into a specified area. Reducing this time also reduces the risk of working too long on a layout alternative that cannot be realised. Realistic visualisation can provide decision-makers with easy-to-understand presentations, enabling decisions based on accurate information. Realistic visualisation also makes it easier and less time-consuming to involve others such as shop-floor personnel, union representatives and health and safety agents in the planning process.

4.3.4 Reflection

The description of traditional layout planning at the Company and its related problems confirms what was found in the two previous industrial studies. Including point clouds in a DES model gave an extra dynamic perspective to the realistic visualisation, compared with the realistic visualisation of Industrial study B. However, at the time of this industrial study, applications for this combination were limited and not fully developed, which meant that modelling the realistic visualisation was difficult and time-consuming. For future industrial studies, the static view with a focus towards how to apply realistic visualisation to support the discussions with risk identification and problem-solving.

Based on the result of the industrial study and what was learned in the previous ones, the research project group suggested using realistic visualisation combined with the LAMDA problem-solving approach of Lean product development. This approach is presented as an iterative process including five steps to solving a problem, which are presented in Figure 4-4 (Ward, 2007). Applying this approach means problems can be solved by evaluating and improving the realistic visualisation systematically in a group of experts, as presented in Table 4-4.

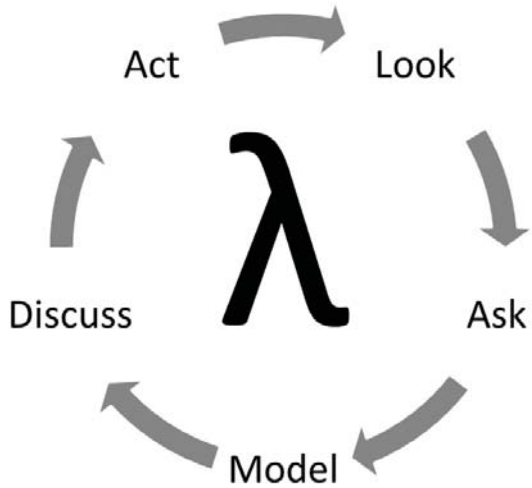

Figure 4-4: The LAMDA approach for problem-solving, adapted from Ward (2007).

Table 4-4: Suggestion of how realistic visualisation can be used in the LAMDA cycle for systematic problem-solving.

Step	**Description of use in industrial settings**
Look	Realistic visualisation affords everyone in the group a common understanding of the redesigned production system.
Ask	Using realistic visualisation will allow qualified assessment of the situation, asking relevant questions and identifying risks or problems.
Model	Changes are made to the realistic visualisation based on identified problems or risks. These might involve moving machines or other equipment, by modifying the point cloud or adding CAD models.
Discuss	The updated realistic visualisation forms the basis of a discussion on defining and analysing solutions and arriving at alternatives for improvement.
Act	The defined solution is implemented in the final realistic visualisation. This is done in the group to verify its effectiveness. The process is then repeated until no further risks or problems are identified.

4.4 Industrial study D

The industrial study was carried out at the Company's main factory in Sweden. Its aim was to further evaluate the possibility of using realistic visualisation for layout planning of production systems, taking a systematic approach to problem-solving. The industrial study was carried out in collaboration with Master's students Olofsson and Sandgren (2015). The industrial study is summarised in this section and presented in more detail in Papers IV and V.

4.4.1 Plan

The industrial study addressed an industrial project tasked with specifying the necessary equipment, tooling, fixtures and workstations and to planning the layout of the production system. The products being made were fabricated sub-assemblies of a structural jet engine component. The scope of the production operations included machining of parts, kitting of parts, fixturing and welding of sub-assemblies, plus machining of the interfaces. The production sequence also included various operations for deburring, cleaning and inspection. The primary equipment functions were four machining centres, one welding cell and one washing machine.

4.4.2 Data collection

The factory building was captured using 3D laser scanning, on an occasion when the area was almost clear of old equipment. Permanent fastening plates for reference spheres were mounted on walls and pillars. The 3D laser scan data was processed to create a point cloud and this was cleaned of unwanted points (representing equipment due to be removed). This point cloud was then combined with 3D CAD models of the new machining centres and equipment, to visualise the planned layout. The machining centre models were delivered from the manufacturer and other equipment was either created or collected from generic model libraries. These models were then located in the visualisation according to a 2D CAD layout created earlier in the project.

Three sequential workshops were held, to evaluate the planned layout. The workshops focused on product and process, installation and maintenance and production sequence. Participant observation was used during these workshops to collect empirical data on how realistic visualisation can be used to systematically evaluate a planned layout. The participants were either working on the design of the production system, or intended to operate it, as presented in Table 4-5. The project leader and engineer responsible for the process and layout took part in all three workshops. This meant they could follow the continuity of the discussions and have a shared understanding of it. Additional participants were two people from the research project and the two Master's students. The research project leader moderated the workshops as a full participant. One of the Master's students controlled the realistic visualisation as a participant-as-observer. The author of this thesis and the other Master's student acted as observers-as-participants and made observations.

Table 4-5: Industrial participants in the workshops.

Workshop	Participant	Work responsibility
1	1	Industrial project leader
	2	Industrial process and layout engineer
	3	Logistics planner
	4	New product introduction leader
	5	Process planner
2	1	Industrial project leader
	2	Industrial process and layout engineer
	3	Machine acquisition
	4	Maintenance engineer
	5	Production facilities engineer
3	1	Industrial project leader
	2	Industrial process and layout engineer
	3	Production leader
	4	Machine operator
	5	Safety representative

The realistic visualisation was used in the workshops to visualise the planned production system layout. This visualisation was evaluated by following the steps in the LAMDA approach, plus a 7-flows process description of the production system (compiled by the Company before the workshops). The design of this evaluation method combines experiences and results from the previous industrial studies, as presented in Figure 4-5. This method allows interactive work to refine the planned production system layout. When a risk or problem was identified, the realistic visualisation and 7-flows process description were changed simultaneously.

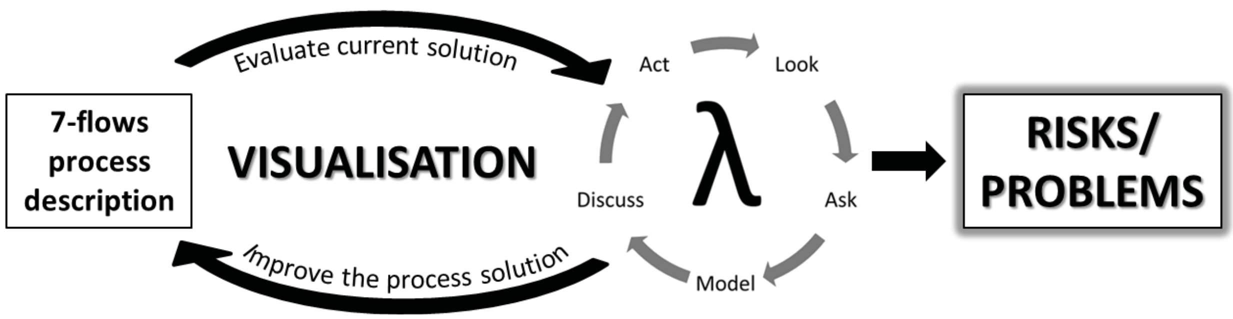

Figure 4-5: Interactive evaluation to refine the planned production system layout.

4.4.3 Results

In this industrial project, the main issue identified with the traditional layout planning method the was the layout's reliance on subjective options rather than facts. The layout was planned using 2D CAD of the shop-floor area and machining centres. This required several manual physical measurements and various layout alternatives were created for the final locations of the machining centres. Producing these alternatives required numerous meetings and many hours of discussions.

The workshops resulted in several risks and problems being identified during systematic evaluation of the realistic visualisation presented in Figure 4-6. Most of these were solved by making immediate changes to the realistic visualisation or 7-flows process description. If the necessary changes and updates could not be made, a risk of possible failure mode was documented and corresponding action taken. The level of severity of some risks and problems was confirmed as acceptable; these were left for monitoring and subsequent mitigation. The most frequent reason for documenting a risk or problem was a lack of exact information, or that something had still not yet been decided.

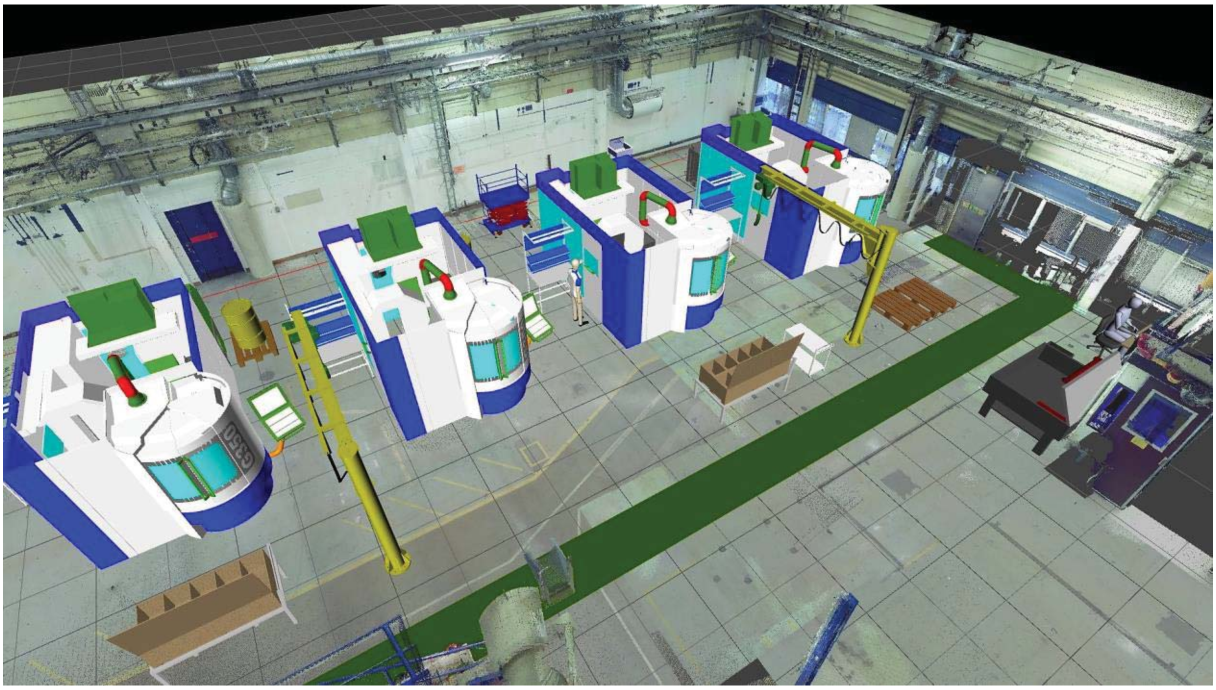

Figure 4-6: Realistic visualisation of the planned production system layout.

In their evaluation, the workshop participants found it useful to move around freely using the realistic visualisation and see the production system from different angles. On several occasions, measurements were made in the visualisation to verify available space or distances. Such evaluation relies on highly accurate input information; an important element in making the correct decisions. It was observed that 3D CAD models showing only the outer dimensions of machining centres might not always provide enough information. Examples of hidden factors to consider included access points for maintenance, transporting routes for swarf containers, cutting fluids systems and other installations. It should be possible to question and confirm the level of detail and correctness.

4.4.4 Reflection

The most important outcome of this industrial study was the workshop structure for systematic evaluation of the planned production system layout. This type of structure is considered able to support the layout planning of production systems, thus resulting in better layouts. Some of the risks and problems identified were highly important to the project. However, the workshop structure needs to be evaluated further to confirm the possible outcomes.

4.5 Overall reflections

The results of the industrial studies show that layout planning of production systems can benefit from using realistic visualisation to support discussion and decision-making. Support was gained from the activities in the industrial studies (conducted in addition to the traditional activities of the industrial projects). These activities focused on how to work systematically with realistic visualisation and were successively improved during the studies. Apart from the documented empirical data, additional knowledge was collected during informal discussions and meetings while working with the Company. The overall appreciation of realistic visualisation at the Company has been positive and the fact that this work has continued at the same company is due to the importance placed by the Company on realistic visualisation.

The industrial projects addressed by the industrial studies lasted up to a year. The rather long durations (and the fact that the studies were involved in various stages of the projects) made it difficult to capture all potential problems and scenarios in addressing the use of realistic visualisation. Ideally, realistic visualisation should be available for the whole duration of these industrial projects. This would allow correct, accurate spatial data on the conditions of the existing factory building to be provided, thus supporting the layout planning early in the project.

The analysis of the empirical data of the industrial studies is summarised as 17 desired functions in a framework for systematic use of realistic visualisation to support layout planning of production systems. How these functions relate to the studies is presented in Table 4-6. These functions cover the problem scenarios identified and lessons learned from applying realistic visualisation during the industrial studies. To some extent, the functions identified may be influenced by those involved in the industrial studies (from both the industrial and academic sides). The industrial project in Industrial study A was selected because it was suitable in time and scope for the research project and because the study participants had been selected due to their involvement in the project. Some of the participants involved were also involved in some of the subsequent studies. Having the same people involved in several studies provided continuity and was preferred when the action research approach was to be adopted. However, it should be borne in mind that the empirical data may have been coloured by these participants. To reduce such bias, each study also involved people who were not involved in the earlier studies and who had no knowledge of the previous results.

Table 4-6: Desired functions identified from Industrial studies A-D.

No.	Function description	Industrial study			
		A	B	C	D
1	Visualisations of production system layouts	X	X	X	X
2	Accurate spatial data of factory buildings	X	X	X	X
3	Visualisations that are realistic and easy to understand	X	X	X	X
4	Visit the factory building virtually	X	X		X
5	Share visualisations within the organisation	X			
6	Visualisations adapted to different type of users	X			
7	Evaluate production system layout alternatives		X	X	X
8	Enhance use of existing 2D and 3D CAD models		X	X	X
9	Move freely within 3D visualisations		X		X
10	Make measurements virtually in factory buildings		X		X
11	Reduce subjectivity by common understanding		X	X	X
12	Discussions in groups with mixed expert knowledge		X		X
13	Involve shop-floor personnel in the design process		X	X	X
14	Apply design changes in visualisation during meetings		X		X
15	Decision-making based on accurate data			X	
16	Structured problem-solving approach			X	X
17	Detailed description of the production flow				X

5 Framework outline

This chapter presents the outline of the framework for systematic use of realistic visualisation to support layout planning of production systems.

The framework for systematic use of realistic visualisation to support layout planning of production systems was outlined to target industrial projects designing production systems in existing factory buildings, to answer RQ2. This framework focuses on the layout planning of machines and other equipment in the production systems. The expected result of using the framework is a production system layout which matches the physical conditions of the factory building. This is achieved by finding and solving potential problems early on in the project timeline.

Industrial projects often follow some type of model. The project model used at the Company was the phase-gate model known as the Information System Global Development Process (IS-GDP). This is a generic model for system development and has some limitations when applied to projects designing production systems. The project model used as the baseline for the framework is the one for production systems design proposed by Därnemyr and Lindell (2013) as part of the Visual Production research project. This model is based on a compilation of the IS-GDP and seven other project models related to production systems design (from theory and other companies). The proposed model divides the project timeline into five stages with eight phases and four milestones, as presented in Figure 5-1.

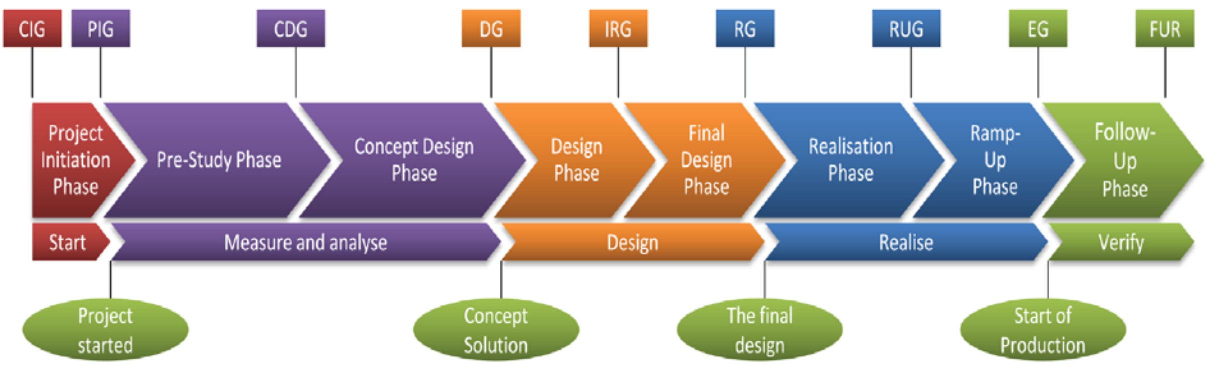

Figure 5-1: Overview of the project model proposed by Därnemyr and Lindell (2013).

5.1 Framework content

From Industrial studies A-D, four design activities can be identified that relate to the 17 desired functions described in section 4.5. These activities are: 1) factory 3D laser scanning, 2) realistic 3D layout development, 3) layout evaluation workshops and 4) process sequence mapping. The relationship between the design activities, industrial studies and functions are presented in Table 5-1. Factory 3D laser scanning was used in all four industrial studies to capture the existing factory buildings and production systems. The scanning process and scan data processing were improved sequentially during the studies. This processed 3D laser scan data is used for realistic visualisation of the existing factory buildings and for developing realistic 3D layouts (combination of point clouds and 3D CAD models). During Industrial studies B-D, various types of these realistic 3D layouts were used to evaluate the layouts. How the layouts were evaluated was sequential development, ending up in the workshops for layout evaluation in Industrial study D. Process sequence mapping can be used to support the layout evaluation by describing how the production will run, which was developed from how the 7-flows process description was gathered by the Company in Industrial study D.

Table 5-1: Design activities related to functions and industrial studies.

Design activity	**Industrial study**				**Function**
	A	**B**	**C**	**D**	
Factory 3D laser scanning	X	X	X	X	2
Realistic 3D layout development		X	X	X	1 and 8
Layout evaluation workshops		X		X	7, 11, 12, 13, 14, 15 and 16
Process sequence mapping				X	11, 12, 13 and 17

The realistic visualisation of the factory building used or created during the design actives can be divided into the three states: 1) as-is, 2) as-planned and 3) as-built. The as-is state describes the current and captured state. The as-planned state describes the planned production system as the project group develops during the project. The as-built state is the final state of the production system after realisation. The as-planned state should be very close to the as-built state, preferably identical. These states can be presented using the types of realistic visualisation (used in the industrial studies) which fulfil the functions. The relationship between the states, type of realistic visualisation and functions are presented in Table 5-2.

Table 5-2: The different states of realistic visualisation, related to the functions.

State	**Realistic visualisation**	**Function**
As-is	Spherical images	3, 4, 5, 6 and 10
As-is	Point cloud	3, 4, 9 and 10
As-planned	Realistic 3D layout	3, 4, 8, 9 and 10
As-built	Spherical images	3, 4, 5, 6 and 10
As-built	Point cloud	3, 4, 9 and 10

The states and types of realistic visualisation are created and used during the design activities, either as input or output. These design activities also have other inputs and outputs to consider, such as data about production and the product to be made. The relationship to each design activity of this input and output data is presented in Table 5-3.

Table 5-3: Design activities and related input and output.

Design activity	**Input**	**Output**
Factory 3D laser scanning *(existing factory building)*	- Physical factory building	- *As-is:* Spherical images - *As-is:* Point cloud
Process sequence mapping	- Product and production data - *As-is:* Spherical images - *As-is:* Point cloud	- Process sequence description
Realistic 3D layout development	- 2D CAD layout - *As-is:* Point cloud	- *As-planned:* Realistic 3D layout
Layout evaluation workshops	- Process sequence description - *As-planned:* Realistic 3D layout	- Process sequence description *(updated)* - *As-planned:* Realistic 3D layout *(updated)*
Factory 3D laser scanning *(after realisation)*	- Physical factory building	- *As-built:* Spherical images - *As-built:* Point cloud

The design activities should be carried out during projects designing production systems to support the layout planning. To outline this framework, the project model suggested by Därnemyr and Lindell (2013) is used for structuring the design activities and for the types of realistic visualisation on a timeline. The design activities and type of realistic visualisation are mainly placed before the final design is set, as presented in Figure 5-2.

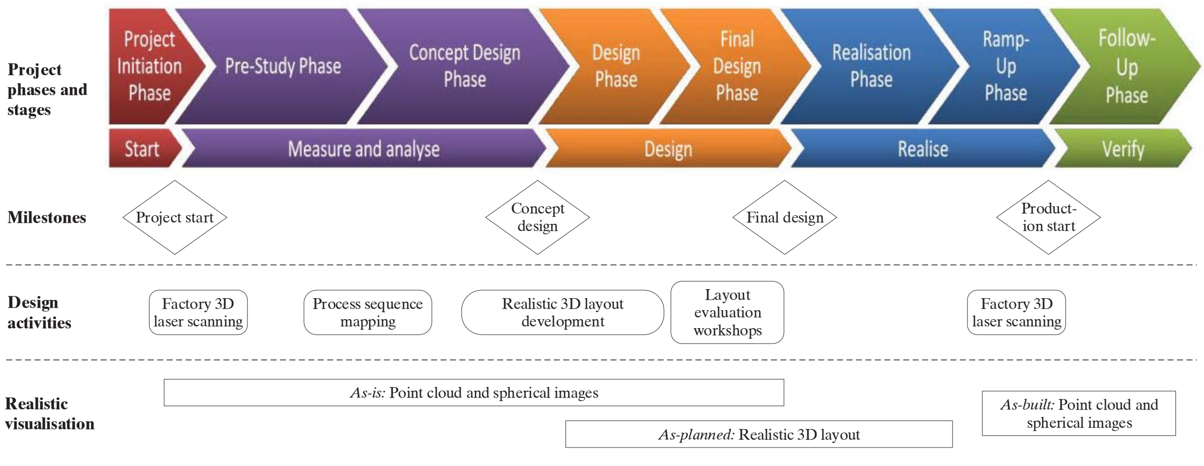

Figure 5-2: Outline of the framework for systematic use of realistic visualisation to support layout planning of production systems (see Appendix for a larger version).

5.2 Description of design activities

The four design activities included in the framework are described in this section. These activities complement existing activities carried out during projects designing production systems and should be combined with them if necessary.

5.2.1 Factory 3D laser scanning

Terrestrial 3D laser scanning is used for capturing the factory building in which the production system will be installed. Preferably, this should be during the project initiation phase, or as soon as the location is decided. After the planned production system is realised, it should be captured once again.

There are several factors to consider when capturing the factory building. To avoid the risk of people disturbing the scan, it should be done when the area is not in use; out of working hours, for example. To ensure good results, it is important to ensure that the area is kept motionless throughout the scan. When planning the scan, a decision should be made as to which parts of the factory building are most important to capture. With that information, the scanner positions can be determined. If reference objects are to be used, these should be mounted relative to the scanner positions. Mounting reference objects on permanent fastening plates allows the same reference positions to be used in future scans. These references can also be used to align the scan data with the common coordinate system within the factory building. For an accurate alignment, the reference objects should be positioned at predefined coordinates. The scanner settings are determined by the specific environment. For example, distance to reference objects and level of details are factors to consider. Higher resolution and quality will increase the scan time needed.

Processing 3D laser scan data is most often semi-automated by using vendor-specific scanner applications or applications which will accept scan data from different vendors. The process involves steps such as combining the different scans, filtering the scan data and applying colours. When all scans are combined successfully, the scan data can be filtered using different parameters to remove unwanted measurement points. Objects in the factory building that will not be kept can be removed from the scan data. After processing the scan data, it can be exported in different file formats depending on how the data is to be used.

See Paper III for a more detailed description and lessons learned from 3D laser scanning of production systems.

Expected result and output

The processed 3D scan data can be used to generate as-is (or as-built if captured after realisation) point cloud and spherical images representing the factory building or production system. The point cloud can be visualised in realistic 3D and is suitable for making further modifications to visualise the planned layout. The spherical images can be used to spread the data throughout the organisation, with the capability to access the data via web browser. The as-built point cloud and spherical images can be used in future development processes and for documentation.

5.2.2 Process sequence mapping

For the planned layout to be evaluated, the process sequence for the production system needs to be known. A method used within Lean production to map existing or future production flows is Value Stream Mapping (VSM). This can provide a visual depiction of the logical flow of a production system (Rother and Shook, 1999). The depiction of the flow is at a relatively high abstraction level. For a more precise definition of the planned production system, the VSM can be complemented with a method based on the 7-flows of manufacturing (raw material, work-in-process, finished goods, operators, machines, information and engineering) (Wroblewski, 2015). The process description of the 7-flows of manufacturing will create a complete and detailed view of the process sequence of the production system. The 7-flows can be supported by 5W2H (who, what, when, where, why, how and how much) to work as a checklist for covering all aspects of the process. Such aspects can be production activities, material supply, defining hardware needs, manpower and skills.

The process sequence mapping can be developed in one or more workshops, with project participants involved in designing the production system. The aim of these workshops is to describe all seven flows in relation to 5W2H, covering the entire production system. This process sequence mapping can, for example, be a table with all seven flows for each step of 5W2H, as shown in Table 5-4.

Table 5-4: Sample table of process sequence mapping.

	Who	What	When	Where	Why	How	How much
Raw material							
Work-in-process							
Finished goods							
Operators							
Machines							
Information							
Engineering							

See Paper IV for a more detailed description of the process sequence mapping.

Expected result and output

The process sequence mapping should result in a description of the planned production system. The description should give project members valuable insight into how the planned production system will run.

5.2.3 Realistic 3D layout development

The as-is point cloud of the existing factory building is used to create a realistic 3D layout to visualise the planned production system. Sections of the point cloud representing equipment not used in the planned production system are removed (or moved, if kept in other locations in the system). The point cloud is combined with 3D CAD models of new machines and equipment; these are usually available from the supplier. The positioning of new machines and equipment can be fixed according to a pre-defined layout in 2D CAD. The development is an iterative process and the project group should be asked for verification of it. If details are found to be missing, the realistic 3D layout should be changed until the project group deems it complete.

Expected result and output
The result is an as-planned realistic 3D layout, which should be true to the physical conditions of the factory building. The point cloud is maintained as a visualisation of the building and objects kept within it. This type of visualisation enhances the opportunities for studying and moving around virtually in the planned production system.

5.2.4 Layout evaluation workshops

Layout evaluation workshops are organised so that the final layout of the production system can be established and the process sequence and operator tasks verified. Hence, the task is to identify and solve risks and problems in the planned layout, before commencing realisation. The process is iterative and divided into three sequential workshops, each targeting specific aims and focus areas, as presented in Figure 5-3. In Workshop 1, the planned product and process sequences are analysed to ensure that all value stream functions are included in the system. Workshop 2 mainly deals with analysing the areas around the machines, to ensure they can be installed and so that necessary maintenance can be conducted. In Workshop 3, the machine operators' work sequences are analysed to establish an efficient and safe work environment. Different participants are invited to each workshop; people who work in the specific focus areas of each workshop. The participants work on either designing the production system or intended to operate it. Ideally, the project leader and those responsible for the layout should participate in all the workshops.

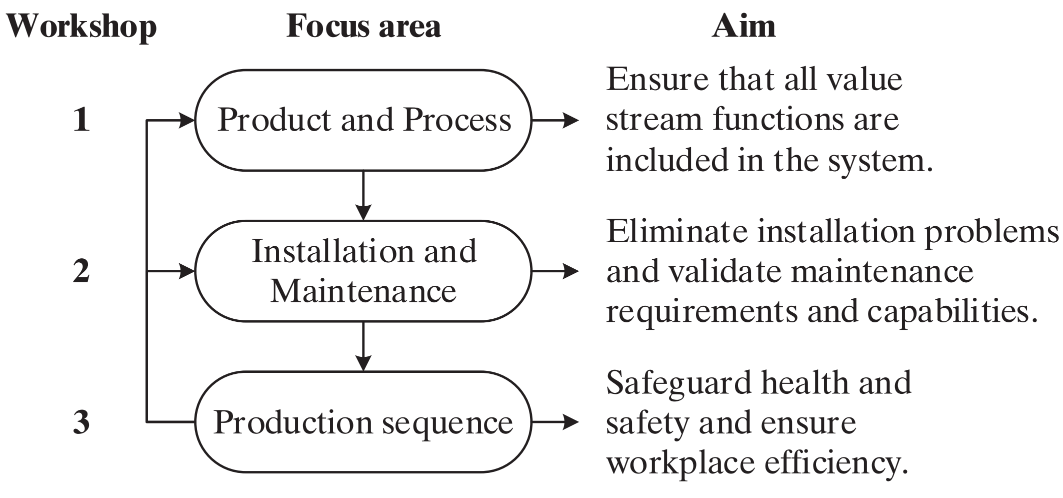

Figure 5-3: Focus areas and aims of the workshops.

The realistic 3D layout and the process sequence description are used to evaluate and analyse the production system layout. A workshop setup comprising two parallel projector screens is recommended for presentation of the realistic 3D layout and process sequence description. The first projector screen is connected to a computer running the realistic 3D layout. The second is used to present the description of the process sequence description or other relevant information. Visualising the content of the process sequence description in the realistic 3D layout allows the LAMDA approach to be used in identifying and solving risks and problems. If possible, risks and problems are solved during the workshop by modifying the realistic 3D layout. Alternatively, modifications may be made between the workshops, to improve the layout according to suggestions from the workshop.

Expected result and output

The layout evaluation workshops should result in an updated and verified realistic 3D layout, capable of being realised in the factory building. The process sequence description should be updated for future use.

6 Framework evaluation

This chapter presents the evaluation of the framework for systematic use of realistic visualisation to support layout planning of production systems. This evaluation was done during the fifth industrial study.

The framework for systematic use of realistic visualisation to support layout planning of production systems was evaluated using Industrial study E, to answer RQ3. As with previous studies, this one was conducted using an action research design, as presented in Figure 6-1. The framework was evaluated by analysing the way it was applied and its impact in supporting the layout planning of an industrial project. The industrial study is summarised in this chapter and presented in more detail in Paper VI.

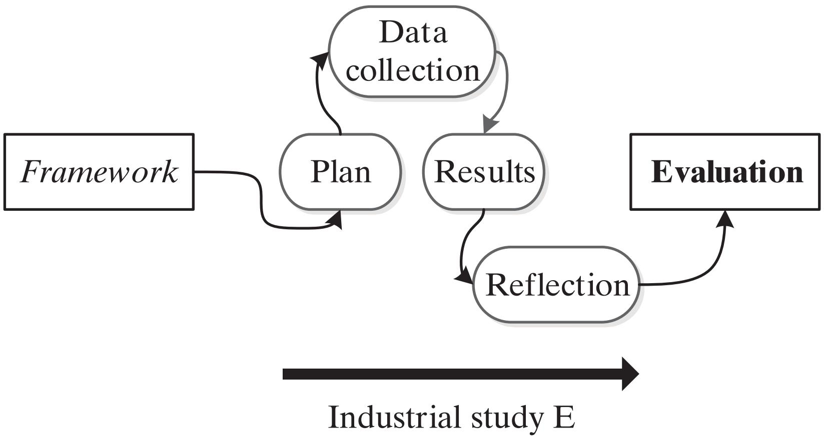

Figure 6-1: Action research applied in Industrial study E for evaluating the framework.

6.1 Plan

The industrial project addressed was designing a production system at the Company's main factory in Sweden. The project examined the production of small parts for use in subsequent fabrication of larger casings; CNC milling being the main production operation. The project was assigned a part of a factory building, with physical limitations and constraints on how to set up the planned production system layout. Other products would also be manufactured in the same area, using both existing machines and some of the forthcoming new ones.

6.2 Data collection

The framework was adapted to fit the needs of the industrial project. The following sub-sections will describe how the design activities were utilised.

6.2.1 Factory 3D laser scanning

The factory building was captured using 3D laser scanning. This was done when some of the old machines and equipment were still in that part of the factory building. Permanent fastening plates for reference spheres were mounted on walls and pillars. The 3D laser scan data was processed to create a point cloud. This was then cleaned of unwanted points, representing the machines and equipment due to be removed. The resulting point cloud consisted of building elements, such as the floor, ceiling, walls and pillars. The removal of defunct machines and equipment resulted in gaps in the point cloud, as shown in Figure 6-2.

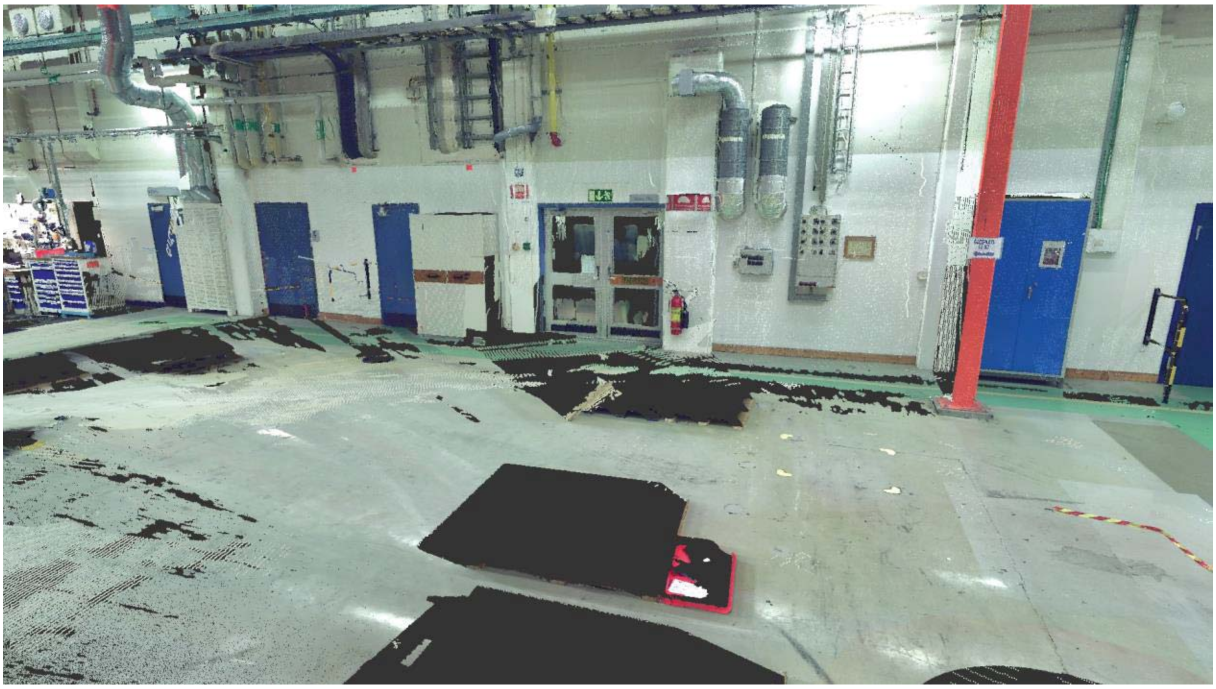

Figure 6-2: Section of the point cloud after removing machines and other equipment.

6.2.2 Process sequence mapping

The industrial project had already partly passed the concept design phase when Industrial study E was initialised. This made the timing of the process sequence mapping unfeasible and therefore not part of the study. The project group was aware of this information, but it was not documented in the structured fashion proposed in the framework description.

6.2.3 Realistic 3D layout development

The realistic 3D layout was developed in two versions, using different applications for viewing on a projector screen or in VR using an HMD. The realistic 3D layout was created using a combination of 2D CAD layout, 3D CAD models and point clouds. The point cloud of the existing factory building consisted mainly of the background environment in the layout. However, some objects (such as the tool trolleys and pallet lifts) were made from a subset of points. 3D CAD models were used to represent new machines and equipment. These point clouds and models were positioned as a realistic 3D layout, according to the 2D CAD layout provided by the industrial project group.

The realistic 3D layout was improved over three iterations. For each iteration, a meeting was held with members of the industrial project. This was to ensure all equipment in the layout was accounted for and that it met their expectations. The first iteration of the realistic 3D layout was discussed with the project leader and a facility project manager. They gave feedback on any details which were missing or wrong and, based on their feedback, additional 3D CAD models were imported into the realistic 3D layout. For the second iteration, the realistic 3D layout was discussed once again with the project leader plus a second project leader. Their feedback was implemented in the layout and a meeting was held to confirm the changes. The third iteration was discussed with a production engineer involved in planning the flow of products. Feedback from this discussion was implemented in the realistic 3D layout. The result was a realistic 3D layout that met the project members' expectations and which had been created using a combination of point cloud and 3D CAD models. This is presented in Figure 6-3. An identical version of the realistic 3D layout was created in an application using VR support, for viewing with an HMD.

Figure 6-3: Realistic 3D layout of the planned production system.

6.2.4 Layout evaluation workshops

The realistic 3D layout was used in three workshops to evaluate the planned layout. Employees from the Company with different competencies and responsibilities participated in the workshops, as presented in Table 6-1. These participants were chosen to match the focus area of each workshop. They either worked in the industrial project group or intended to operate the production system. In addition to the workshop participants, four researchers were present from the research project conducting the industrial study. The research project leader moderated the workshops whilst acting as a full participant. One researcher managed the realistic 3D layout; responsible for making changes to the layouts as needed and acting as a participant-as-observer. The author of this thesis and another researcher made observations but did not take part in the discussions; their role was observers-as-participants. Written observation notes were taken and audio was recorded.

Table 6-1: Industrial participants in the layout evaluation workshops.

Workshop	Participant	Work responsibility
1	1	Project leader
	2	Process planner
	3	Production leader
2	1	Project leader
	2	Process planner
	3	Machine acquisition
	4	Maintenance engineer
3	1	Project leader
	2	Process planner
	3	Production leader
	4	Team leader/machine operator
	5	Machine operator
	6	Machine operator

The setup involved two parallel projectors and an HMD. The first projector showed the realistic 3D layout, while the second one showed additional information, such as product and production data. The realistic 3D layout was presented in VR using an HMD with two hand-held controllers for navigation and user interaction.

The workshops were introduced by the moderator. The process planner than gave a presentation of the production and material flow. Discussions were held between the participants, using a laser pointer when discussing specific details in the realistic 3D layout on the projector screen. Measurements provided true and accurate information; this was used to analyse the space for operators and other resources. Available space for various resources was evaluated. For example, the number of pallets that could be stored in the incoming material area was analysed by importing and locating pallets into the area until it was filled. A top view of the layout was used to gain an overview. From this angle, the 2D CAD layout was then enabled, so that other sections of the factory could also be visualised.

The HMD was used for viewing the realistic 3D layout during the second half of Workshops 2 and 3. One participant at a time wore the HMD and held the controllers to interact with the visualisation. What they saw was displayed on the projector screen for the other participants.

The risks and problems identified were mostly solved within a minute, by moving or importing equipment into the realistic 3D layouts. These changes were then instantly evaluated using the LAMDA approach. Risks and problems that could not be solved during the workshops were noted by the project leader for further investigation.

6.3 Results

The framework was used in a research context to support the industrial project in its layout planning. This resulted in an improved final production system layout, compared to the one initially created. Additional improvements were limited to existing prerequisites, such as machine foundations.

The 3D laser scan of the factory building resulted in an accurate virtual representation of the existing factory building, with its machines and equipment. The point cloud generated from the 3D laser scan data covered the most essential part of the factory building. However, some data was missing, due to the removal of machines and equipment. This point cloud enabled the creation of a realistic 3D layout for use in realistic visualisation of the planned production system layout. The main obstacle to this realistic 3D layout was a lack of 3D CAD models for some pieces of equipment. This was because they were unavailable or not currently specified by the project group.

The workshops were appreciated and the usefulness of discussing a realistic 3D layout was obvious to all participants. The involvement of stakeholders outside the project group (such as machine operators) meant that potential risks and problems were identified which had not previously been discussed. A total of 15 risks and problems were identified, as specified in Paper VI. These were mostly solved during the workshops.

The group felt that the HMD offered better perception of proportions and distances, compared to viewing the realistic 3D layout on the projector screen. Awareness was heightened by the "wow factor" that users had in experiencing the novelty and realism of a realistic 3D layout. The heightened perception and awareness of the users resulted in such benefits as identifying locations for information screens and determining the proper work heights for tables.

6.4 Reflection

The design activities in the framework increased the transparency of the planned layout for those in the industrial project group and those who would be working in the production system. One reason for this increased transparency is that realistic visualisation enhances the communication with those who will be working in the production system; gaining their opinions and acceptance.

If the framework were to have been applied from the start of the project, more changes could likely have been made. However, it is difficult to measure the value of using the framework and, for a full evaluation, the framework should have been used for the entire industrial project. Had the framework been utilised during the entire project, the design activities would have been a natural part of it and may have reduced the time needed for other activities (which would have been supported by realistic visualisation). These include the development of the 2D CAD layout and other issues related to physical conditions of the factory building.

Not all risks and problems could be solved during the layout evaluation workshops and this may indicate a need for a further iteration of them. The main reason these risks and problems were not solved was the missing information from those who did not take part. The result of the workshops relates to the roles of the participants and how the production flow is presented and understood. As the process sequence mapping was not part of the industrial study, there was no structured way to describe the production and material flow during the workshops. This may have caused mistakes and a lack of information. In a future realisation of the framework, process sequence mapping needs to be carried out (or equivalent information should be available before the workshops are held).

The HMD used for viewing the realistic 3D layout in VR had not been used in previous industrial studies. This type of HDM has shown promise before, but only now is the technology mature enough for use in industrial settings. On the downside, the “wow factor” can lead to users being less critical and thus missing details. One example of this from the industrial study was a missing guard rail; this could give a misleading impression of available space. The user’s impression might have been different, had that guard rail been in place. The guard rail was also missing in the realistic 3D layout presented on the projector screen, but was noticed during the third workshop.

7 Discussion

This chapter discusses the results in relation to other research in the area, the research approach and potential future research.

The aim of this thesis was to outline and evaluate a framework for systematic use of realistic visualisation to support layout planning of production systems. This aim was addressed by the three RQs, the answers to which are summarised in Table 7-1. RQ1 was answered by identifying the 17 desired functions in a framework based on the outcome of Industrial studies A-D. The research contribution of these functions was to identify the basic needs and drivers from an industrial perspective. The functions were used to outline the framework, which was based on design activities and realistic visualisation used in Industrial studies A-D. The outline of the framework answers the RQ2 and its research contribution is to complement the theoretical approaches to production systems design with up-to-date technologies. RQ3 was answered by the evaluation results of the framework, using Industrial study E. Its research contribution was to provide the outcome of utilising the framework.

Table 7-1: Summary of how the RQs were answered.

	RQ1	**RQ2**	**RQ3**
Result	The 17 desired functions in the framework.	A framework for supporting layout planning using realistic visualisation.	Benefits and challenges of utilising the framework.
Research contribution	Industrial needs and drivers for support in layout planning.	Complementing theoretical approaches with how to use up-to-date technologies for layout visualisations.	Providing an idea of the possible outcome of utilising the framework.

7.1 Supporting layout planning

The benefits of 3D laser scanning in capturing factory buildings and generating accurate virtual representations within hours is shown in the five industrial studies. This verifies other work done within the area, for example, Shellshear et al. (2015) and Simonsson and Johansson (2015). Other technologies for capturing factory buildings can also be used, but 3D laser scanning was found most suitable and is already used in some industries (Shellshear et al., 2015). Opportunities for processing and using 3D scan data have changed during the lifetime of this research. The main changes are increased computer performance and improved applications, making it possible to work straightforwardly with point clouds of factory buildings on a laptop. An example of an improved application is the method for combining scans. This has changed, from reference objects being required to a cloud-to-cloud combination in which scans are combined by matching their overlap. Cloud-to-cloud combinations require less time in the factory for the scanning. However, reference objects can still be important if the coordinate system is to be reused or recognised in the factory, as exemplified in Shellshear et al., (2015) who discusses incremental scanning of factory buildings for long-term documentation.

The virtual tools used for layout planning in manufacturing companies are usually a matter of in-house tradition and changing this can take a long time. As described in the industrial studies, the type of virtual tools used for layout planning were 2D CAD layout applications. Such layouts have been shown to have two types of problems. Firstly, they lack crucial details and are not always accurate and true to the factory building. The positioning of objects in the 2D CAD is not always true to the physical positioning, as exemplified in Paper VI and Stoli and Rex (2014). Secondly, people's awareness and understanding of such 2D CAD layouts is low, as described in Iqbal and Hashmi (2001) and shown in several of the industrial studies. To increase awareness and understanding, layouts can be presented in 3D. The realistic 3D layouts used in the industrial studies proved that some areas of the production system became visible which had not appeared when using 2D CAD layouts. 3D provided the opportunity to analyse layouts from different angles and put the user into a third-person perspective. This reduces the gap between the ideal layout and the actual one and can be related to whether there was the opportunity to consider and understand the constraints at the start of layout planning (Schenk et al., 2005).

Dahl et al. (2001) describe how previous experience and knowledge can interfere understanding virtual representations. When evaluating a planned production system layout, this interference can be seen when people focus on their expert area. For example, machine operators focus on the area around their machine. This diverse focus is utilised in the layout evaluation workshops, where the main aim is to gain ideas from people with different focus areas. A downside is the need to deal with more opinions, which may result in more discussion. To make such discussions objective, a realistic visualisation needs to be accurate and true, otherwise, there is a risk of communicating incorrect information. The guard rail that was missed in Industrial study E, for example. This might have created a misunderstanding about there being enough space available. Understanding can also be related to how realistic visualisation is presented. For example, the difference between how a projector screen and an HMD present an understanding of available space. As described by Smith and Heim (1999), VR can create rapid and accurate decisions, but if incorrect information is presented such rapid decisions can lead to problems.

It is important to work collaboratively and systematically on identifying risks and problems with the planned layouts as early as possible. As stated by Pehlivanis et al. (2004), visualisation is important to collaborative work and is a central part of the design activities within the framework. Collaborative work creates the opportunity to include people in the organisation who have different roles and knowledge. Covering various aspects of the production system has been highlighted as important if the layout is to be evaluated properly. Realistic visualisation of spherical images of 3D laser scan data is one example of how the as-is state of the factory building can be shared within an organisation. This creates awareness for everyone involved. If the information is easy to access, people can use it in their daily work of designing the production system. Moreover, it is important to inform other parts of the organisation, to gain acceptance and make people aware of the opportunities being offered.

7.2 Industrial utilisation

The project model used for outlining the framework addresses an overall project view of production systems design. This is described by Chryssolouris (2006), among others, as a complex process involving several different people and focus areas. The framework includes a sequence of design activities which support the layout planning in establishing evaluated production system layouts. Such design activities allow realistic visualisation to be used for discussion and decision-making. The framework does not replace the overall project model used for projects designing production systems. Rather, it should serve to complement such a model or be included in existing ones. This type of process is not generic; it differs depending on the organisation utilising the framework. The way in which realistic visualisation is used will depend on the organisation but, used in the right context, it can facilitate the desired support. The context may be the design activities of the framework or related activities.

This thesis has strived to bring industry new knowledge and aids for layout planning of production systems. As shown by the industrial studies, the benefits of using realistic visualisation are continuously enhancing the understanding of such possibilities. The evaluation of the framework in Industrial study E highlighted the opportunities to utilise the framework in an industrial setting. The complete framework (or parts of it) can be utilised, depending on needs and requirements. On an overall level, the framework is outlined in such a way that design activities and realistic visualisations can be used in industrial settings by adapting to the needs of the organisation implementing it. However, there are still barriers to consider before implementing the framework. In a scenario where the framework is applied, those involved in such a project should be required to participate in the design activities.

7.3 Research quality

The relevance, reliability and validity of qualitative research has been discussed and may not be suitable for all type of research methods (Bryman and Bell, 2011). The discussion relates to issues such as measuring the reliability of qualitative data. The qualitative data collection methods used in this thesis may be difficult to replicate identically. Creating the same environments with the same people will be difficult and, if it were to happen, there would be a bias from previous research. However, in a similar context and with the same data collection methods, the result might be the same. Documentation of the methods is described as important to replication and forms a major part of the framework in this research. For example, Industrial studies D and E, in which the methods and results of Industrial study D were repeated and evaluated.

The validity of the research has been tested and evaluated using the eight categories for validity testing provided by Maxwell (2005) and, as stated, not all categories are relevant to all types of research. The following categories are relevant to this thesis:

- *Intensive, long-term involvement:* the author of this thesis was involved in the research projects throughout the entire process. During that process, there was close collaboration with the Company resulting in a good relationship. This relationship led to informal discussions and feedback during the industrial studies. In turn, the informal discussions and feedback form part of the empirical data collected by long-term observation. This made it possible to change the data collection direction and methods along the way and thus adapt to the needs of the framework.
- *Respondent validation:* many people from the Company were involved in several of the industrial studies and a few people in all of them. This involvement created a continuous validation of previously collected data and the framework.
- *Intervention:* realistic visualisation and 3D laser scanning for layout planning were new to the Company when the first research project was initialised. Along the way, the Company has discovered some benefits and there is internal interest in using the technology.
- *Triangulation:* the main part of the design activities was iterated and validated through the first four industrial studies, where different data collection methods were used. The empirical data is supported by the literature, in which the problem formulation was similar to those in the industrial studies. In evaluating the framework, there may be some bias due to such an evaluation covering only one industrial study.

7.4 Future research and recommendations

The continuation of this research should focus on utilisation of the framework. As part of the utilisation, it should be decided who will own 3D laser scanner equipment and carry out the scanning. This was a recurrent discussion during the industrial studies. Manufacturing companies have two main alternatives to carrying out 3D laser scanning. Either own the equipment and have trained personnel within the organisation do the scanning, or buy in the service from a consultant firm. Both alternatives have pros and cons that need considering in relation to the needs of the organisation. The framework and design activities (such as 3D laser scanning) need to be distinct elements of the project model used within the organisation. As for the design activities, these can be extended and may not be limited to the one in the framework.

The author of this thesis believed that 3D laser scanning or similar technologies for capturing the factory buildings will become an even more valuable tool in production systems design. Both in redesigning existing production systems and in designing new ones. Keeping an updated 3D laser scan data of the existing factory building would improve the day-to-day development and changes to a production system. However, such updates require structured work routines for updating the data and distributing it throughout the organisation.

The use of HMD to visualise production system layouts has the potential to increase user awareness. It is recommended that the same realistic 3D layout is used, depending on the aims of the presentation are. Otherwise, additional work is required to prepare diverse types of realistic 3D layouts to adapt to the different technologies.

8 Conclusion

This chapter presents the conclusions drawn from the research.

This thesis outlines and evaluates a framework for systematic use of realistic visualisation to support layout planning of production systems. The framework is outlined based on 17 desired functions identified from four industrial studies. These functions include accurate 3D laser scan data of the factory buildings to obtain realistic visualisation, and to support the layout planning of production systems. Realistic visualisation enables virtual factory visits to existing and planned production systems. Such virtual factory visits have been shown as important in individual engineering tasks and in project group meetings, decision-making and problem-solving concerning planned production system layouts.

The framework includes design activities and realistic visualisation mapped to a project model timeline for production systems design. The layout evaluation workshops are one of the main design activities. These are held to ensure that realisation of the planned production system layout is possible. Evaluation relies on realistic 3D layouts, which enable decisions to be made based on accurate facts and information.

The benefits of utilising the framework are shown in all five industrial studies and relate to the opportunity to ensure decisions are taken based on a spatially accurate layout of the production system. This requires a management-level change of the project procedures for designing production systems. At the utilisation stage, it is important to target this level because, without the acceptance and interest of management, there is a risk that the utilisation will fail.

Manufacturing companies which utilise this framework have the potential to make correct decisions on layout, avoid costly problems and reduce overall project times. The strength of the framework lies in the way it works systematically and virtually throughout the entire design process. This enhances overall understanding and awareness of the existing and planned production system layouts. Spreading this understanding within the project group and among others involved in the production system will provide evaluated production system layouts.

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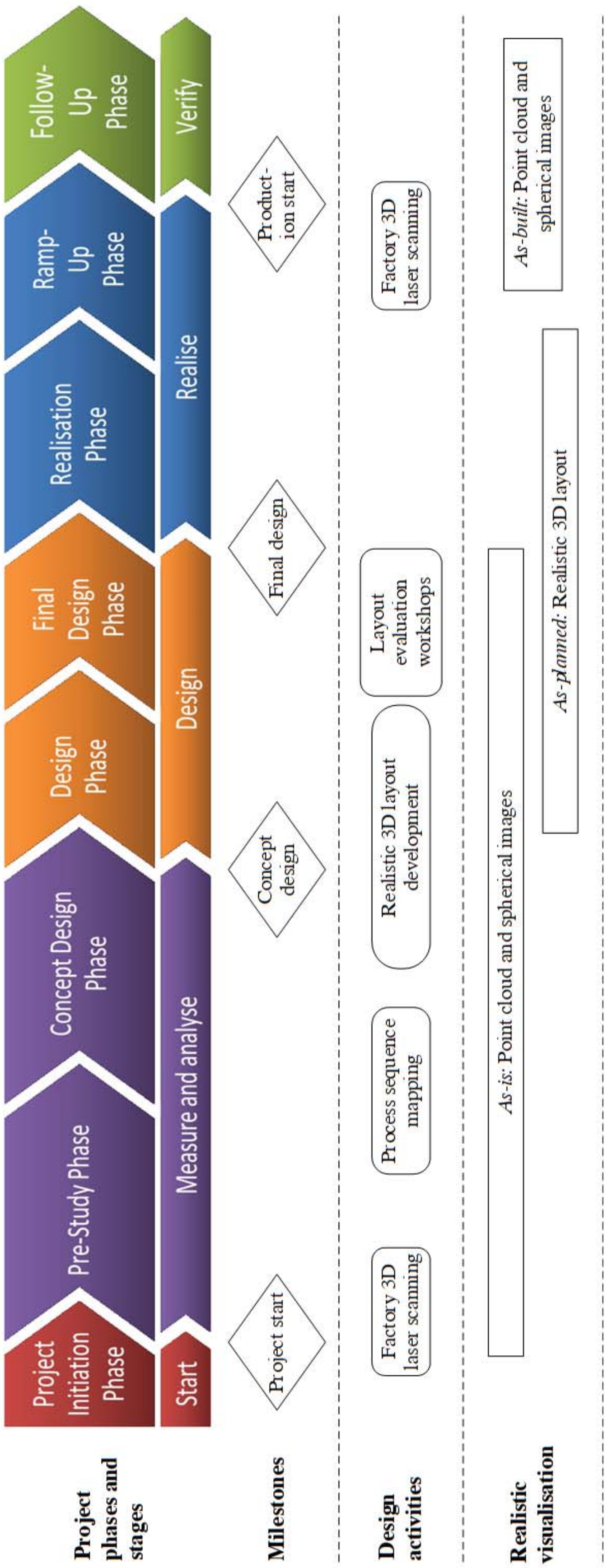
Appendix


Project phases and stages
Milestones
Design activities
Realistic visualisation
Project Initiation Phase
Pre-Study Phase
Concept Design Phase
Design Phase
Final Design Phase
Realisation Phase
Ramp-Up Phase
Follow-Up Phase
Start
Measure and analyse
Design
Realise
Verify
Project start
Concept design
Final design
Product-ion start
Factory 3D laser scanning
Process sequence mapping
Realistic 3D layout development
Layout evaluation workshops
Factory 3D laser scanning
As-is: Point cloud and spherical images
As-planned: Realistic 3D layout
As-built: Point cloud and spherical images